Final Overview of ACES Simulation for Evaluating SARP Well-Clear Definitions

Confesor Santiago

8/5/14 – 8/7/14

Supported by Marcus Johnson, Doug Isaacson, and David Hershey

Overview

- Review Traffic Scenarios
- Overview of Well-Clear ACES Simulations
- Review of Well-Clear Definitions within Autoresolver
- Lessons Learned
- Results

But First…

“Parallelisms of weak-side defense in basketball and UAS DAA systems”

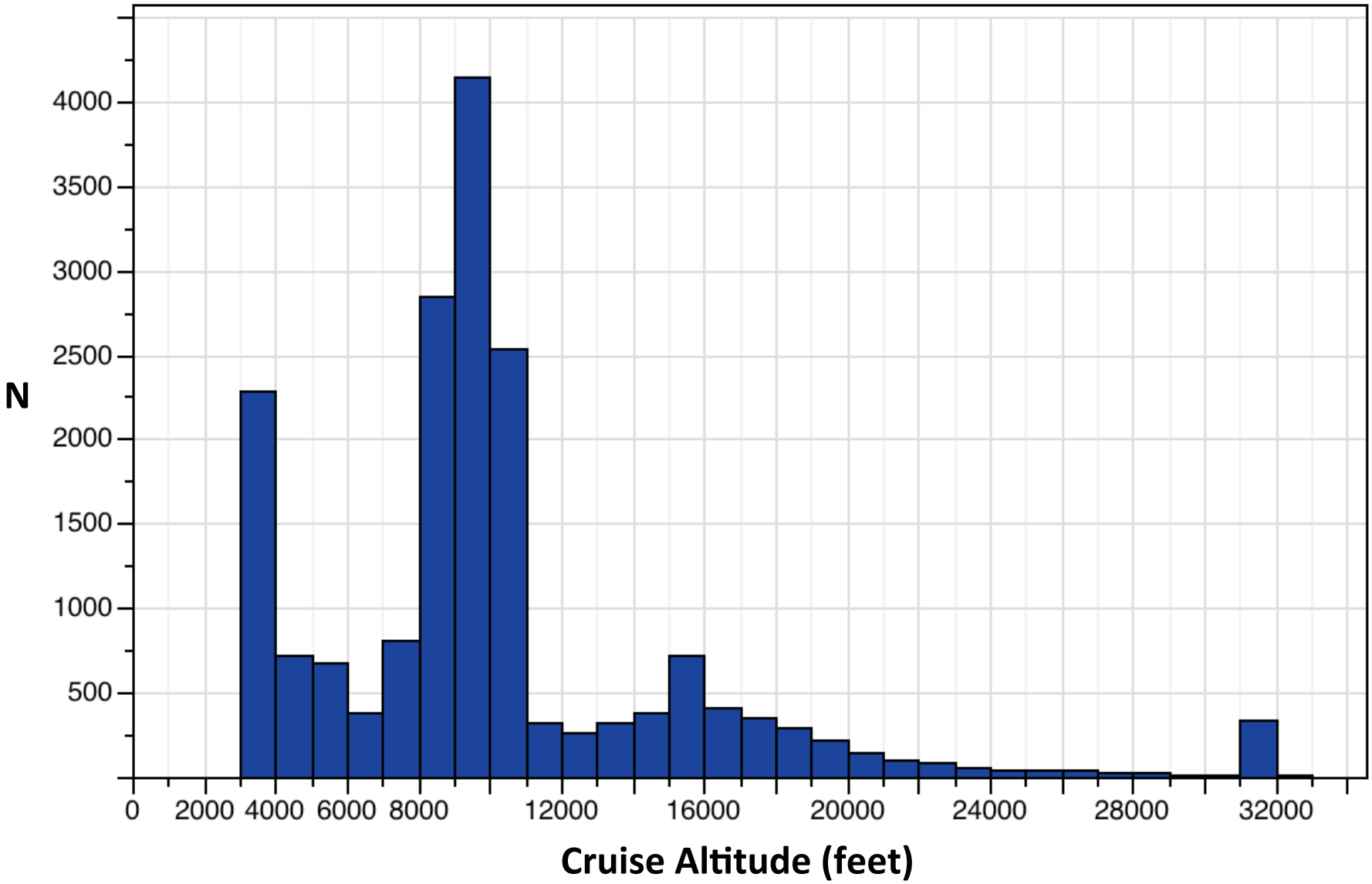
- Flight hours
- Big sky theory
- Lack of intruder intent
- Maneuvering trajectories
- Limited field of regard
- Aircraft performance

UAS Missions

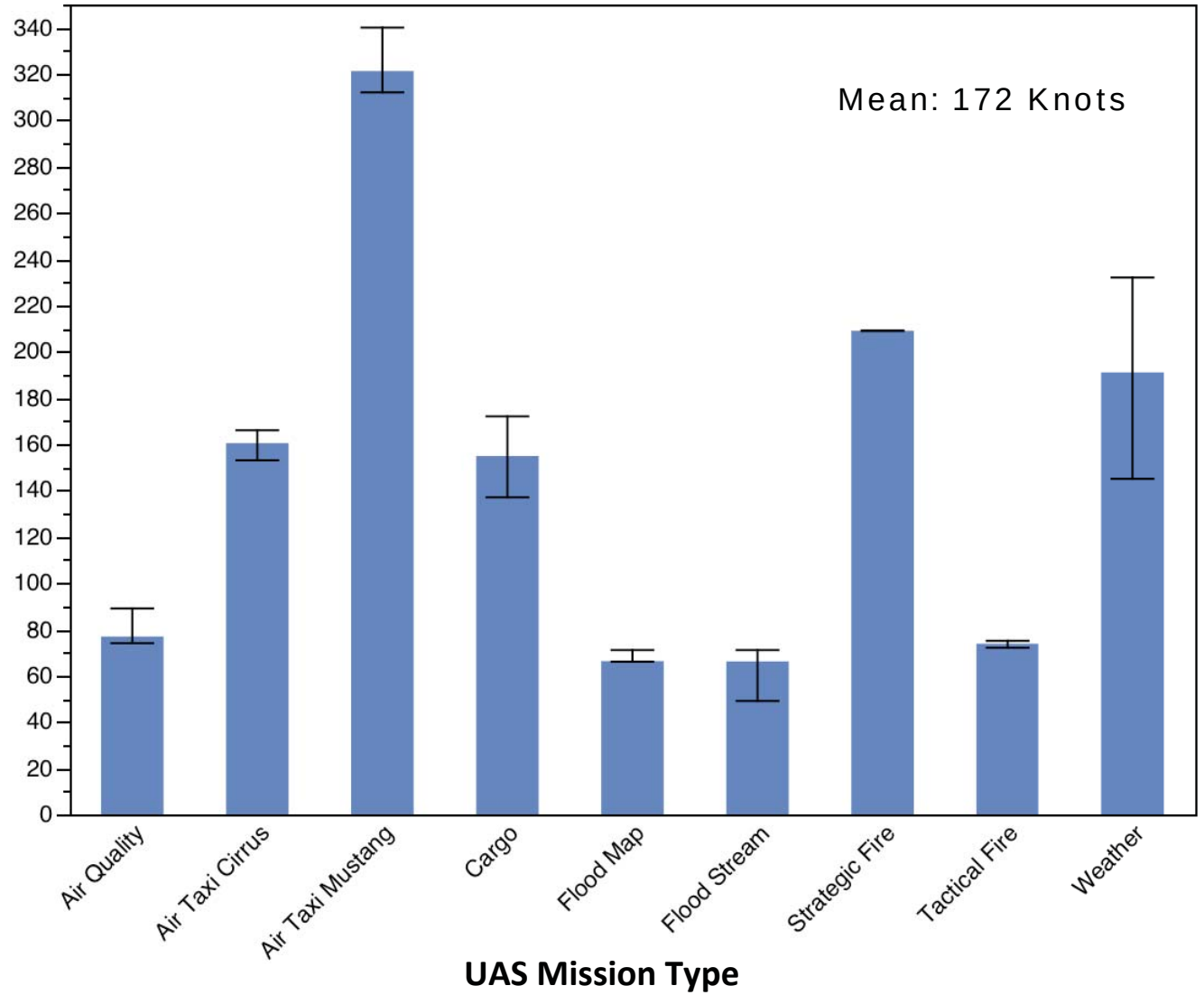
- Atmospheric Sampling
  - Global Hawk (RQ4-A) [2350 flights]
- Border Patrol
  - Global Hawk (RQ4-A) [665 flights]
- Cargo Transport
  - UAS Cessna 208 [1320 flights]
- Strategic Wildfire Monitoring
  - Predator B (MQ-9) [325 flights]
- Air Quality Monitoring
  - Shadow-B (RQ7B) [1050 flights]
- On-Demand Air Taxi
  - Cessna Mustang (C510) [2560 flights]
  - Cirrus (SR22T) [10500 flights]
- Flood Mapping

Total UAS Flight Hours in a Day: 25,734

UAS Cruise Altitudes



UAS Cruise Speeds



Cooperative VFR Traffic

- The 84th Rader Evaluation Squadron (RADES) data were used.
  - The data contain the radar hits collected from hundreds of radar sites in U.S, and each hit provide timestamp, latitude, longitude, Mode 3 code, Mode C code, and others.
  - There is no explicit information that could be used to determine whether radar hits come from IFR flights or VFR flights.

- Criteria for filtering out VFR traffic (for each tracked flight):
  - All tracks are below 18,000 ft,
  - At least one track has the Mode 3 code of 1200,
  - Average speed ranges from 50 knots to 250 knots.

- Non-cooperative VFR radar track coming soon…

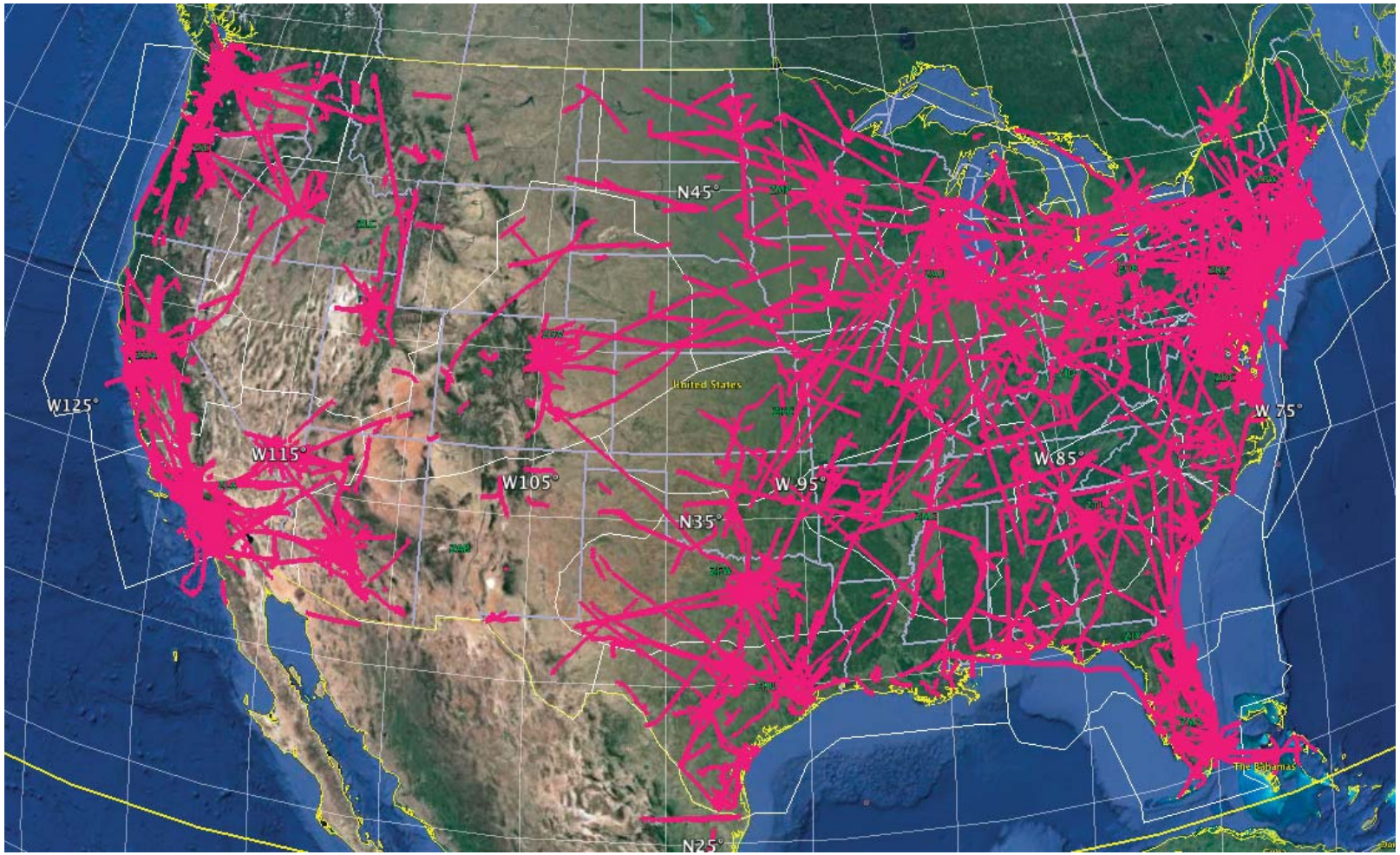
Method for Extracting VFR Traffic

- Input: RADES data for a certain time period.

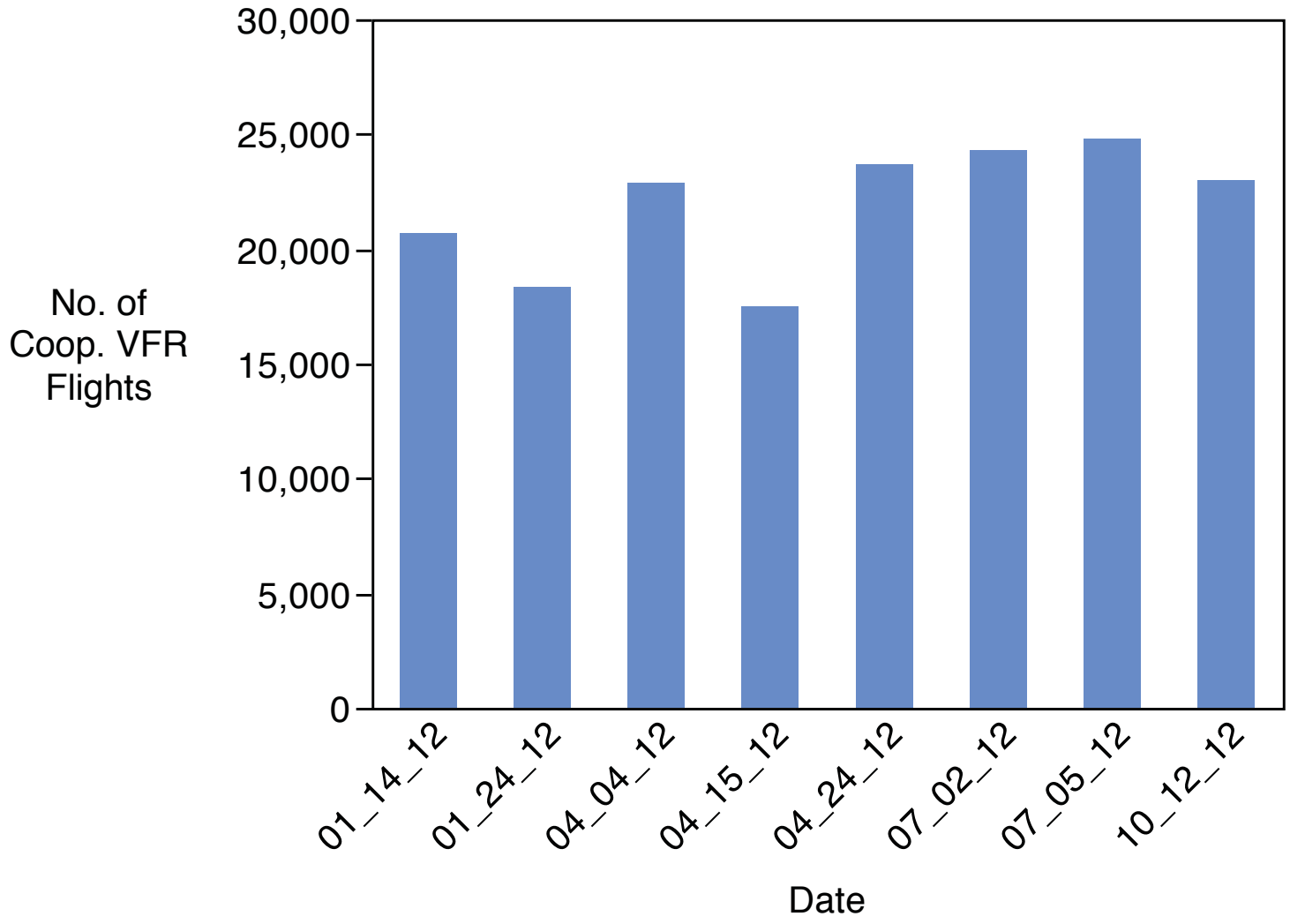
- Output: Flight plan file for a fast-time simulation system, Advanced Concept Evaluation System (ACES).

- Method (three steps):
  1. Generate tracks using a minimum spanning tree based clustering algorithm,
  2. Generate smooth tracks using a Kalman filter,
  3. Generate a flight plan file after reducing the number of waypoints and adding airports which are closest to start/end waypoints.

Cooperative VFR Traffic – July 25, 2013



Cooperative VFR Traffic Days Used



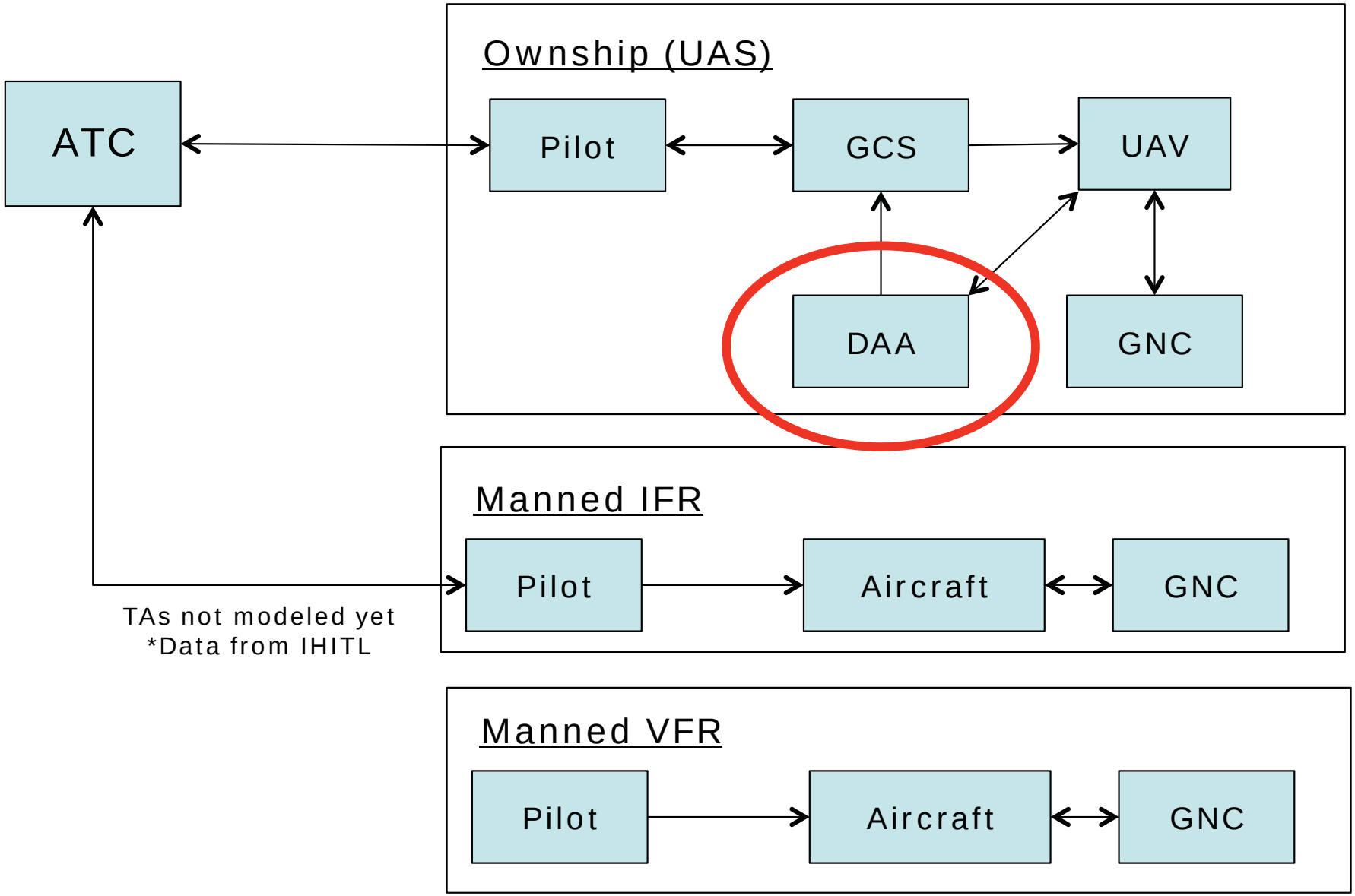
ACES Simulated Traffic

- ACES simulates flight paths of UAS mission using:
  - Departure times
  - Source and destination airports
  - Flight plan (route, cruise speed and altitude)
  - "UAV-like" aircraft models
- ACES simulates flight paths of cooperative VFR traffic using:
  - Departure times
  - Source and destination airports
  - Flight plan (route, cruise speed and altitude)
  - "GA-like" aircraft model

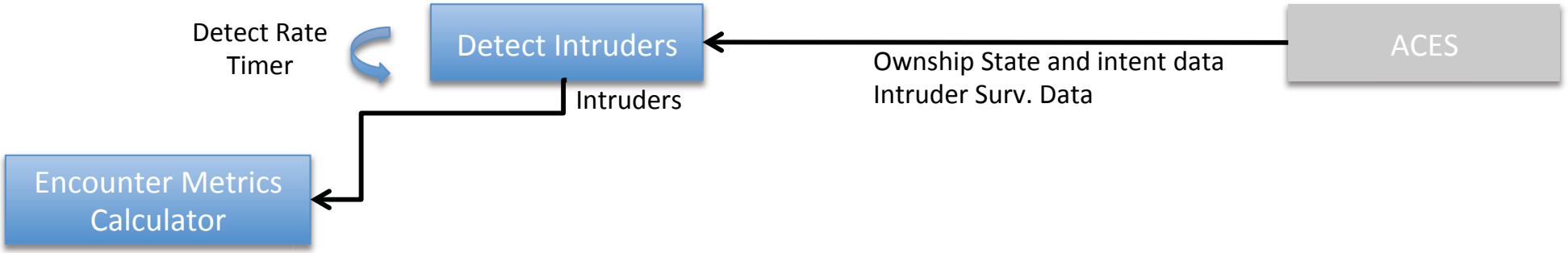
Well-Clear ACES Simulations

- ACES agent-based distributed architecture
- Typical configuration is running across three servers with 36 CPU-threads and 360 GM RAM
- Each UAV aircraft is modeled by an “agent”, and balanced across the 36 CPUs
- Within the agent a DAA “activity” was added that is configured to accept all truth states with a “gross” filter distance at a parametric detect rate
  - 2-second detect rate
  - 30 nmi range

Well-Clear ACES Simulations



DAA Architecture (Unmitigated)

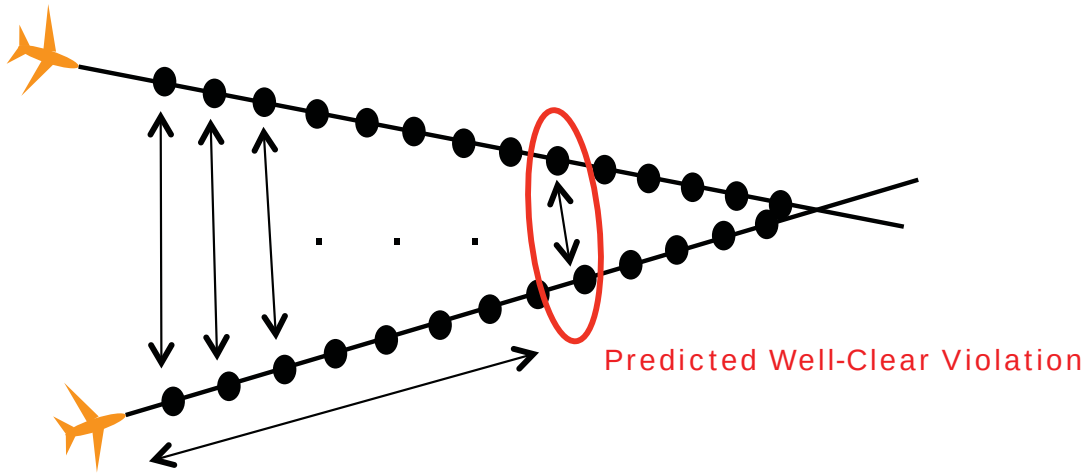


Measures:

- ModTau
- VertTau
- TimeToCpa
- HMD
- VMD
- rDot
- hDot
- Range
- relX
- relY
- relZ
- relHeading

Integration of Well-Clear Definitions into Autoresolver

- Three well-clear definitions have been integrated into Autoresolver
- At every detect cycle, 2-minute trajectories for ownship and intruder are built
  - No sensor uncertainty
  - Only intruder position and velocities are known
- If well-clear violation is predicted to occur within a parametric time (SST), Autoresolver is triggered to generate an avoidance maneuver
  - Due to maneuvering intruders, or bends in UAV route structure may detect before the SST



Autoresolver Resolution Logic

- Detect well-clear violations with at 60 seconds SST
- A prominent feature of Autoresolver is during re-evaluation, trajectories for maneuver are built until SST plus buffer
  - E.g. detect at 60 seconds, and recommend resolution predicted to be threat-free for 120 seconds
- Another prominent feature of Autoresolver is adding buffer to horizontal separation
  - E.g. scale horz. separation by 25%
  - Usually no need to add buffer to vertical domain, because procedural significance of vertical clearances (cardinal altitudes)
- Lastly, for NASA and MIT-LL well-clear definitions, Autoresolver tries to maneuver to achieve well-clear via vertical or horizontal miss distance, modTau not considered, but TCOA is

Autoresolver Resolution Logic (cont.)

- Searches for the minimal left/right turn and climb/descent that resolves the WCV, i.e. respective WCV threshold plus a 25% scaling in horizontal
  - Integrates 5 degree turns, and 500 ft altitude increments
- Minimizes deviation, i.e. minimum cross track and vertical deviation plus buffers
- Resolution heuristic prefers horizontal maneuver when ownship is at level flight
- Prefers vertical maneuvers if the ownship is non-level
- In the event of tie in maneuver deviation, turning right or descending is preferred

Lessons Learned

- WCV with VFR traffic may end and start close to each in time
  - Merge if WCV between same aircraft pair is within 120 seconds

- Time to co-altitude's utility not realized given limited number of high vertical closure rate encounters

- P(TCAS-RA|WCV) is high at TCAS Sensitivity Level 6 (Alt: 10,000 – 20,000) for all WC definitions
  - Parameters of TCAS model thresholds are outside NASA and MIT-LL

TCAS RA Model Altitude Dependent Thresholds

Own Altitude (ft)	SL	Tau (sec)	DMOD (nmi)	ZTHR (ft)	ALIM (ft)	HMD (ft)
1000 - 2350	3	15	0.20	600	300	1215
2350 - 5000	4	20	0.35	600	300	2126
5000 - 10000	5	25	0.55	600	350	3342
10000 - 20000	6	30	0.80	600	400	4861
20000 - 42000	7	35	1.10	700	600	6683
> 42000	7	35	1.10	800	700	6683

MIT-LL uses 0.66 nmi

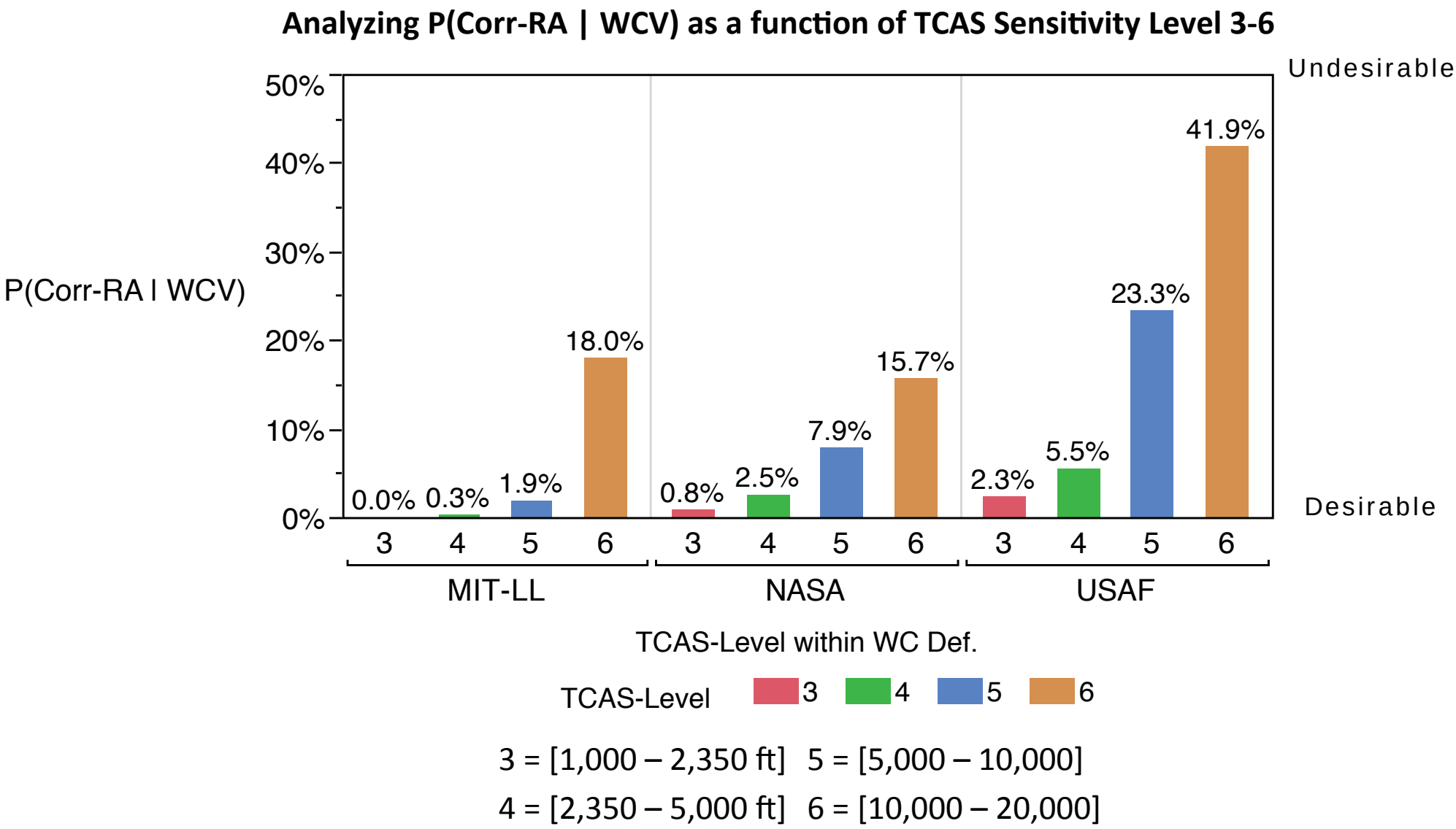
NASA uses 20 TCOA

NASA uses 475 ZTHR

** Source: "A TCAS-II RESOLUTION ADVISORY DETECTION ALGORITHM," Cesar Muñoz, Anthony Narkawicz, and James Chamberlain, AIAA Guidance, Navigation, and Control Conference, 2013. Table 1: TCAS Sensitivity Level Definition and Alarm Thresholds for RAs*

Final Results (Unmitigated)

P(Corr-RA|WCV) Unmitigated ACES Result



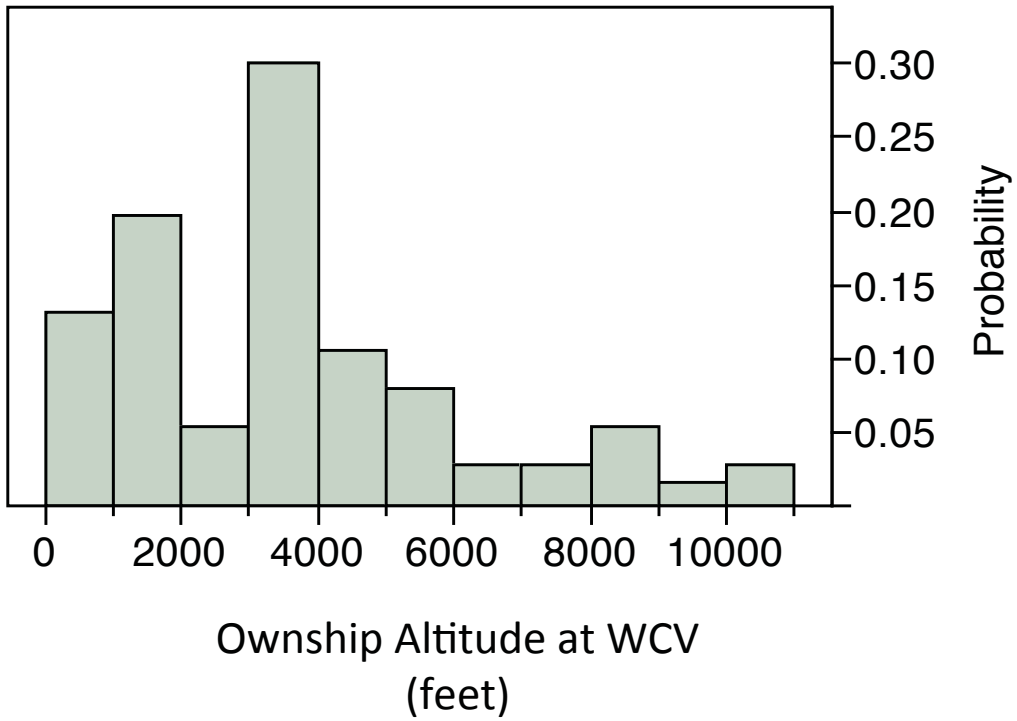
3 = [1,000 – 2,350 ft] 5 = [5,000 – 10,000]

4 = [2,350 – 5,000 ft] 6 = [10,000 – 20,000]

P(NMAC|WCV)

- NASA = 1.17%
- MIT-LL = 1.23%
- USAF = 1.37%

Ownship Altitude at NMAC



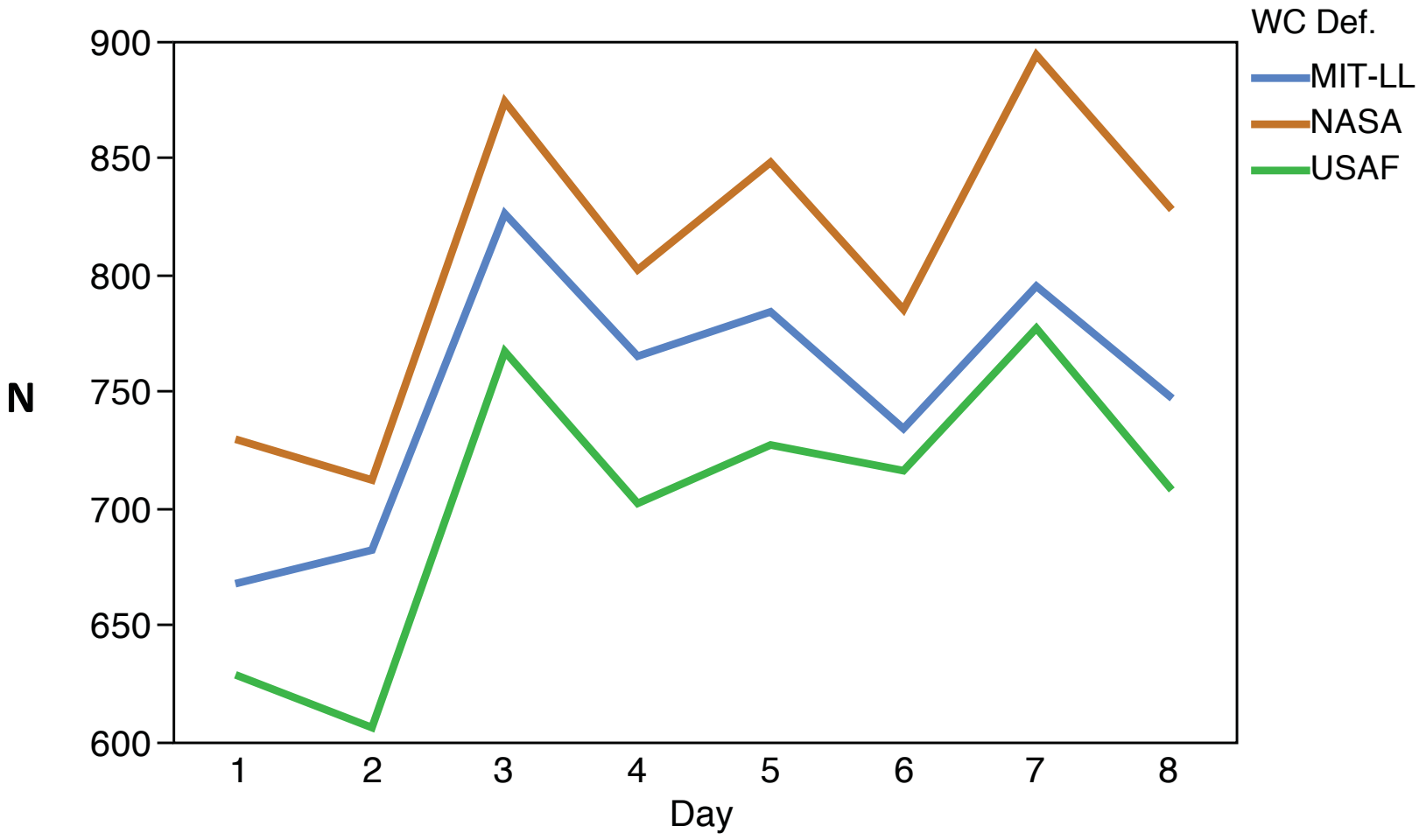
Quantiles

100.0%	max	10000
99.5%		10000
97.5%		10000
90.0%		7733.6
75.0%	quartile	4416
50.0%	median	3274
25.0%	quartile	1615
10.0%		899
2.5%		798.15
0.5%		782
0.0%	min	782

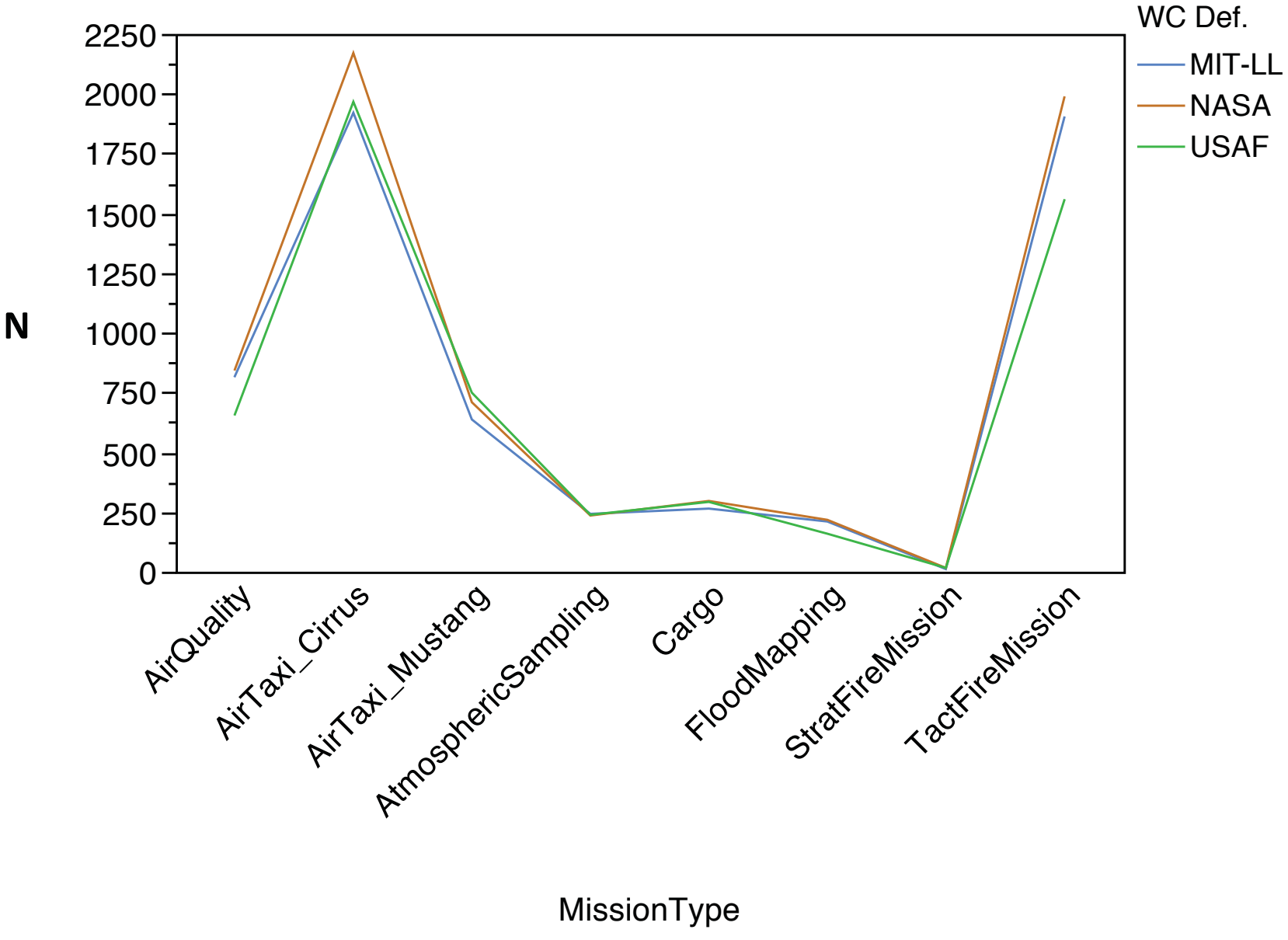
Summary Statistics

Mean	3564.2338
Std Dev	2300.1527
Std Err Mean	262.12673
Upper 95% Mean	4086.3044
Lower 95% Mean	3042.1631
N	77

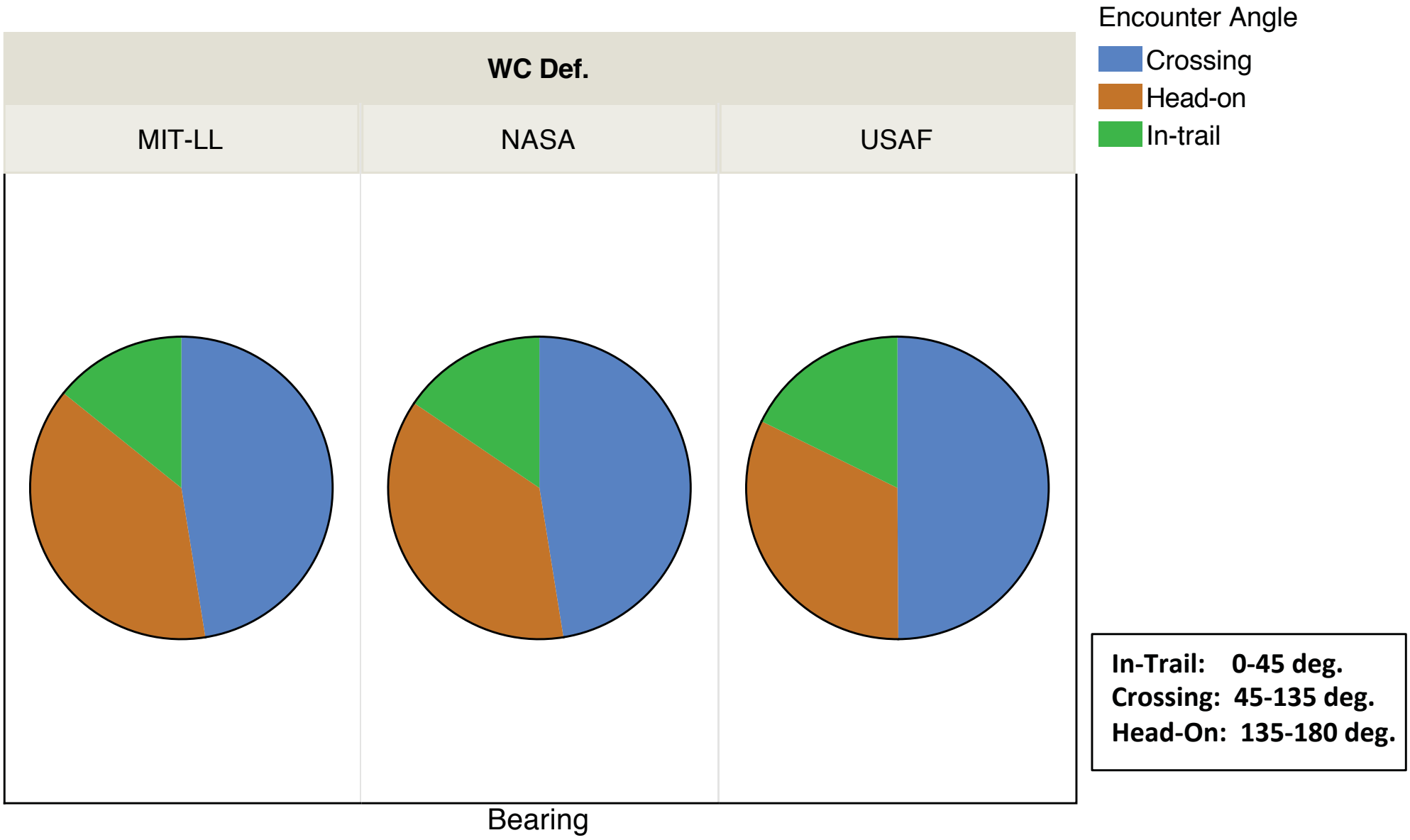
No. of WCV per Day per Definition



No. of WCV by UAS Mission

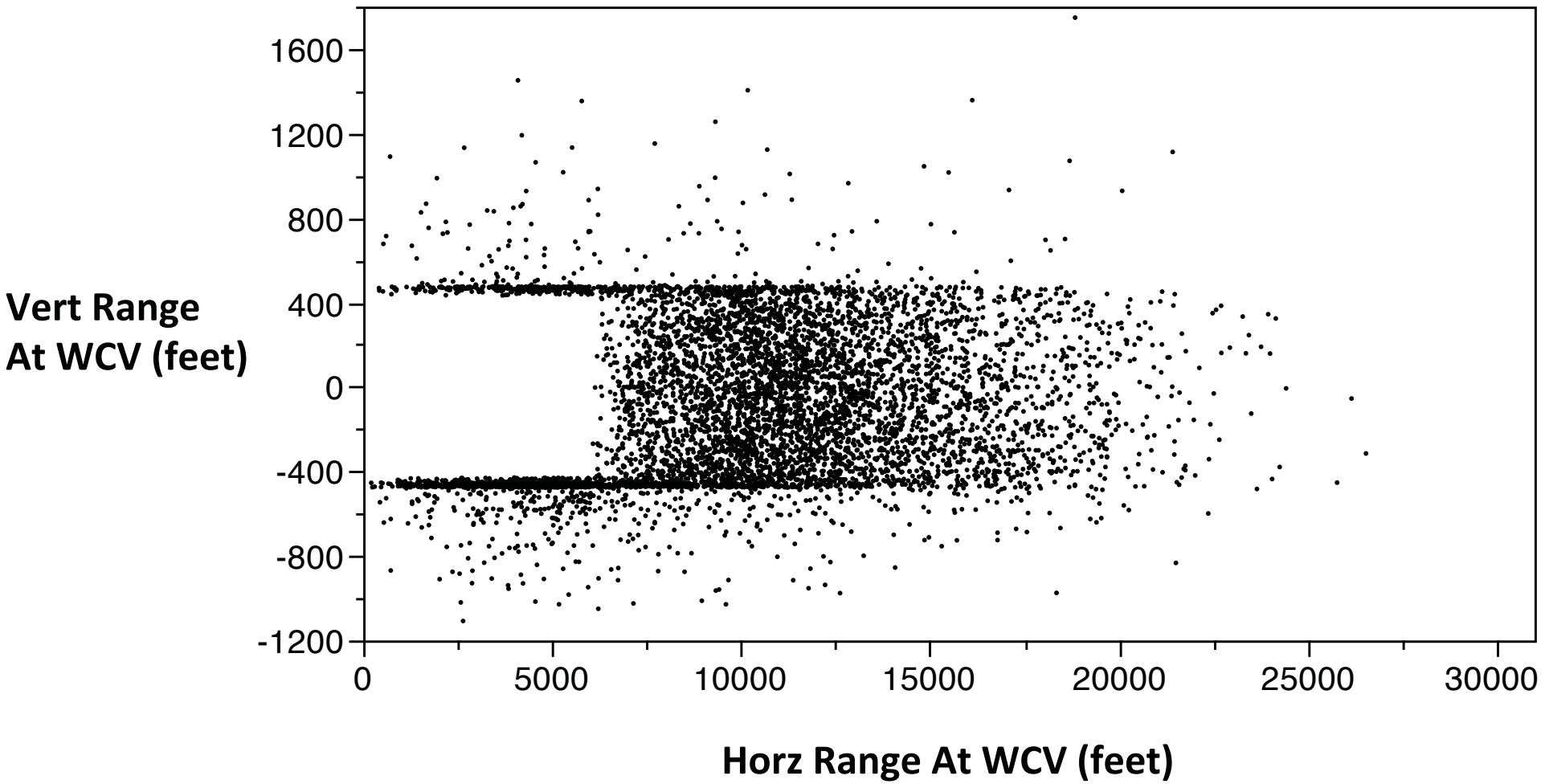


Encounter Angle at WCV



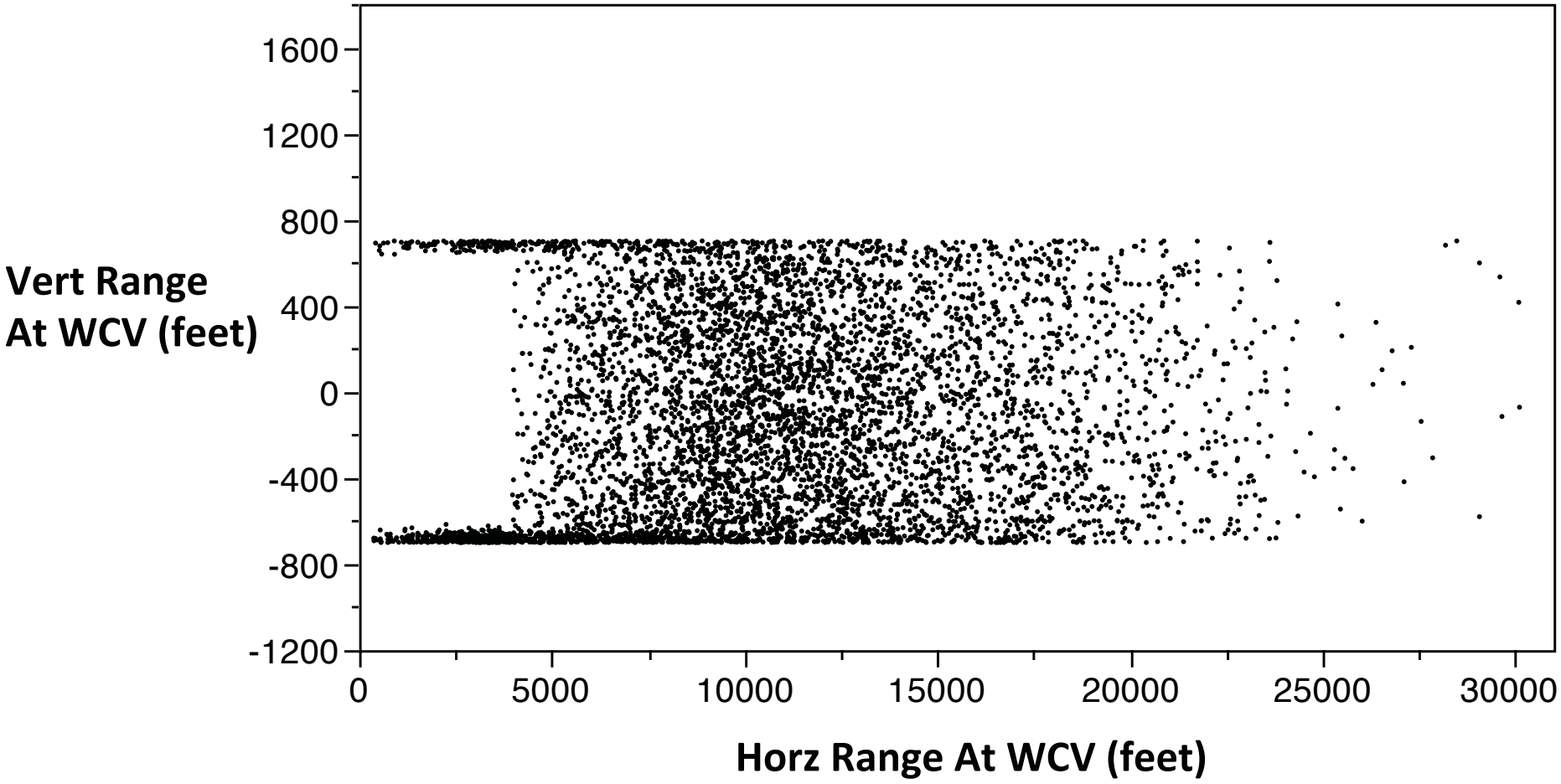
In-Trail: 0-45 deg.
Crossing: 45-135 deg.
Head-On: 135-180 deg.

Horz. And Vert. Range at WCV - NASA



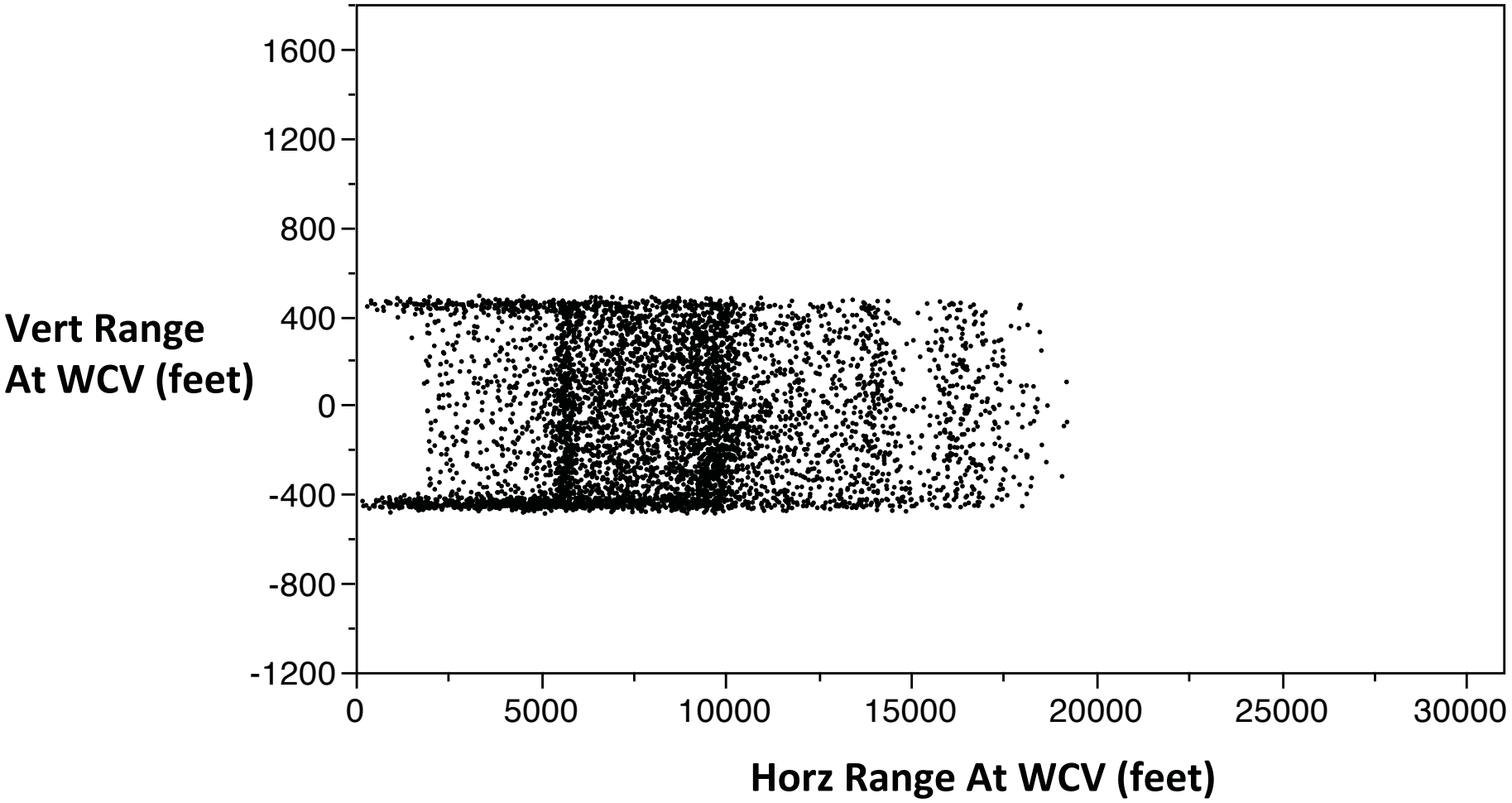
- Larger vertical range is due to time to co-altitude.
- High vertical range and low horz. range may be difficult for RADAR to detect

Horz. And Vert. Range at WCV – MIT-LL



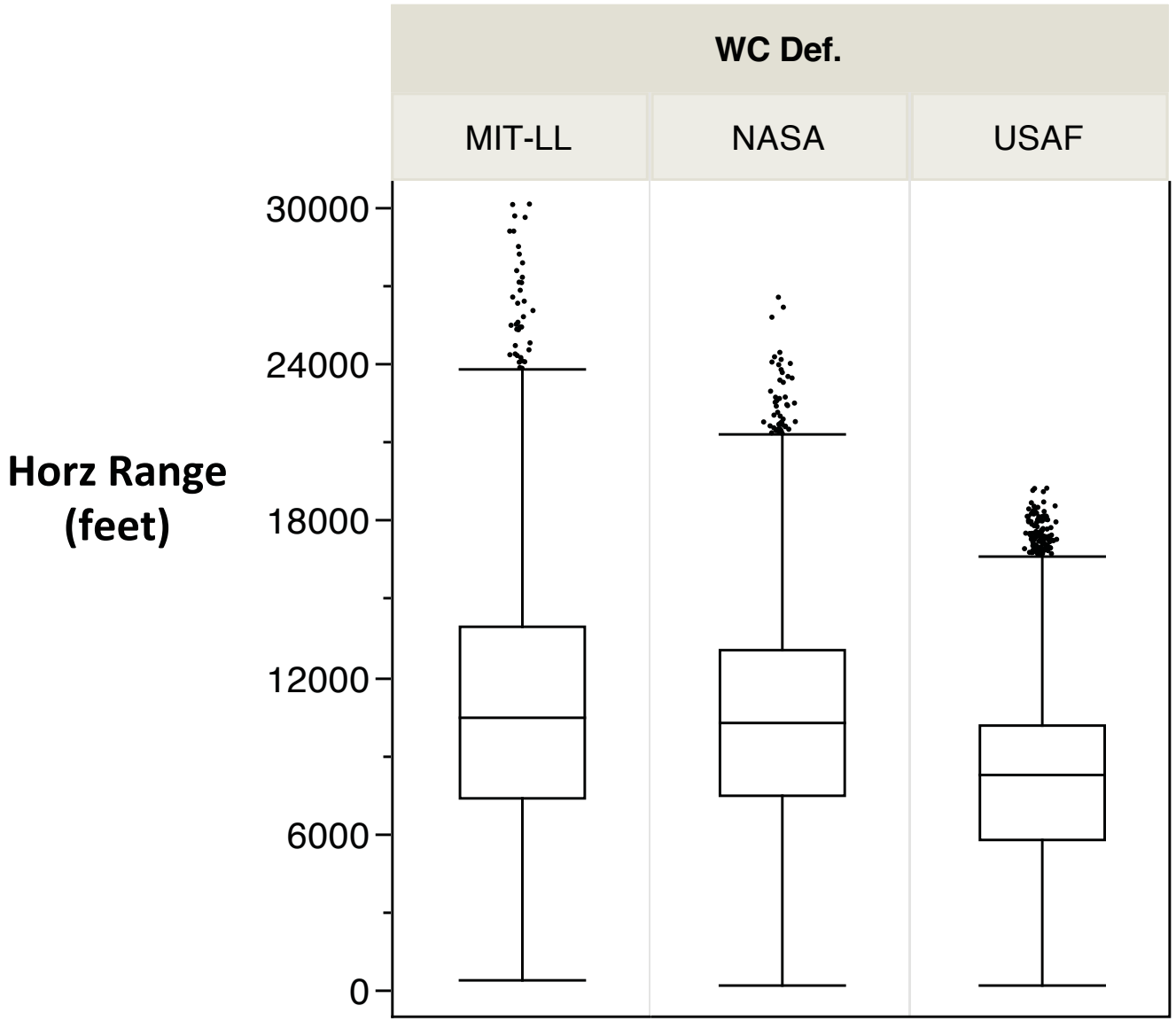
- Larger horz range is expected due to larger modTau
- Lack of TCOA threshold makes vertical range truncated at 700 ft

Horz. And Vert. Range at WCV - USAF

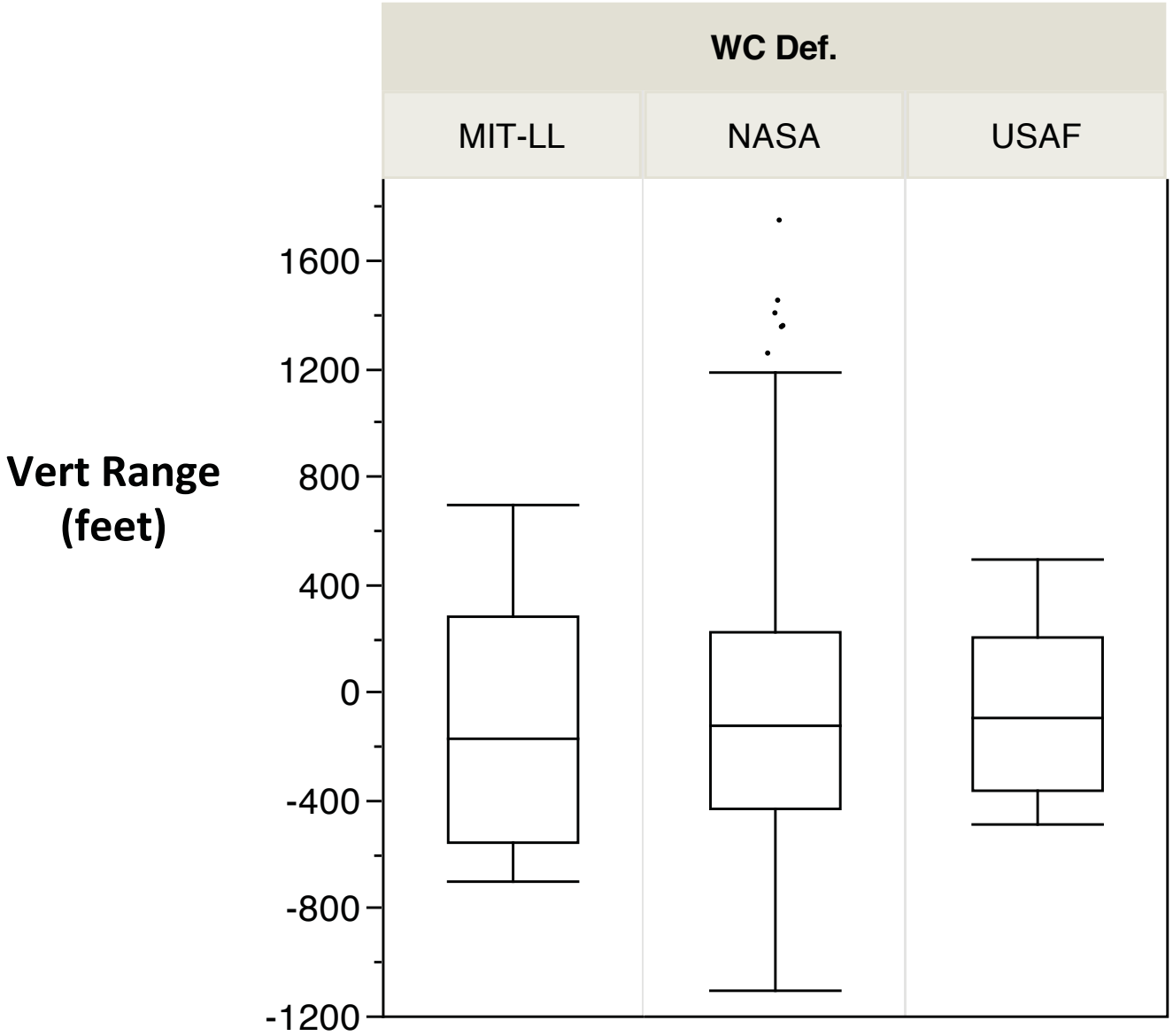


- Much shorter ranges, positive for sensor requirements

Horizontal Range at WCV



Vertical Range at WCV



ModTau/Time-to-co-altitude Model

Question: How often does time to co-altitude get triggered with NASA WCVs?

```
[( r <= DMOD) or
      ((0 <= tau_mod <= tau_thresh) and
      (HMD <= HMD_thresh))]

      and

[(h <= ZTHR) or
      (0 <= vert_tau <= tau_thresh)]
```

NASA Definition Violation Probability

N(WCV)	P(ModTau_TCOA)	P(DMOD_TCOA)	P(ModTau_ZThr)	P(DMOD_ZThr)
6473	1.3%	1.2%	80.8%	16.7%

Key:

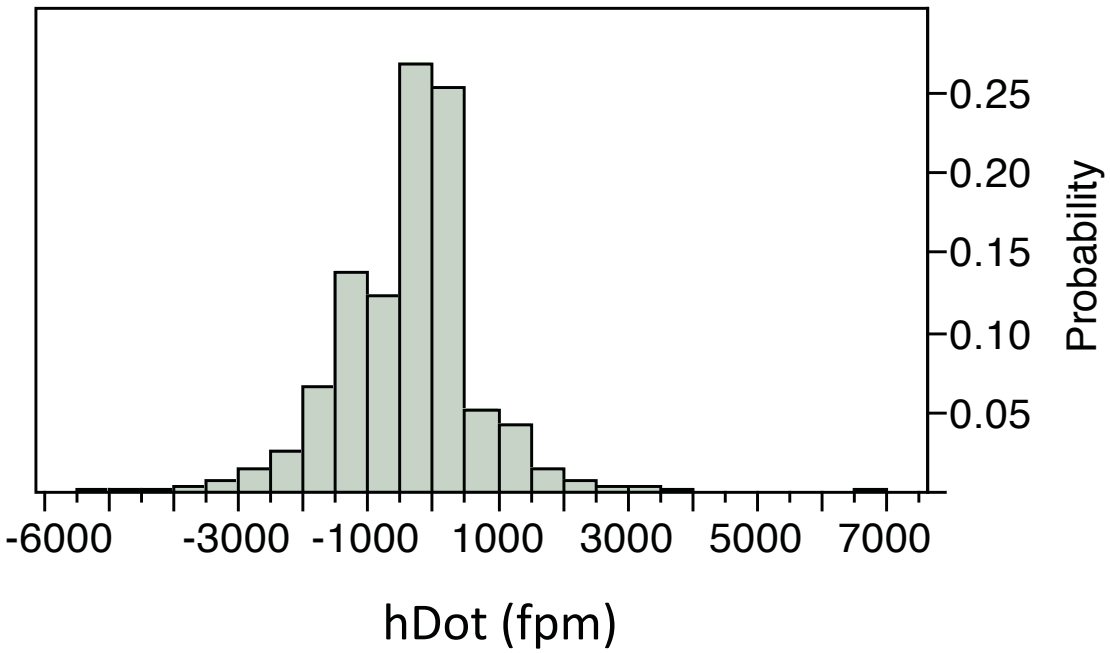
ModTau_TCOA: WCV occurs with modTau and TCOA

DMOD_TCOA: WCV occurs with DMOD and TCOA

ModTau_ZThr: WCV occurs with modTau and ZThr (not TCOA)

DMOD_ZThr: WCV occurs with DMOD and ZThr (not ModTau or TCOA)

hDot (vertical closure rate) – NASA



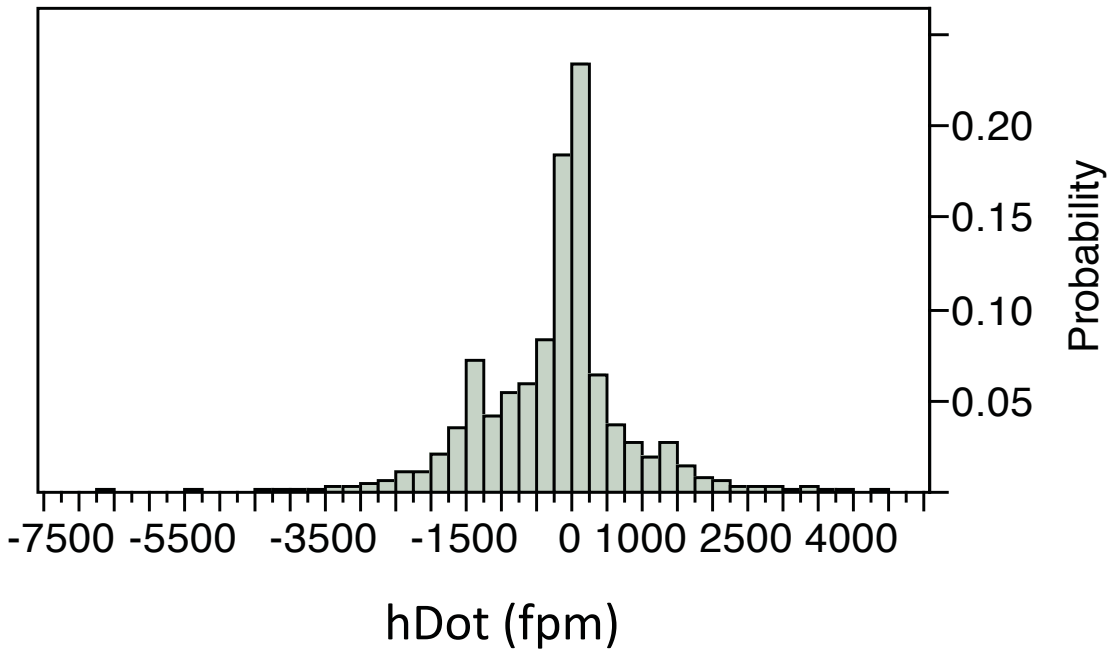
Quantiles

100.0%	max	6665
99.5%		2359.94
97.5%		1465.3
90.0%		609.601
75.0%	quartile	46.9998
50.0%	median	-151
25.0%	quartile	-985
10.0%		-1562.6
2.5%		-2377.6
0.5%		-3174.8
0.0%	min	-5268

Summary Statistics

Mean	-375.2541
Std Dev	948.14354
Std Err Mean	11.784775
Upper 95% Mean	-352.1521
Lower 95% Mean	-398.3562
N	6473

hDot (vertical closure rate) – MIT-LL



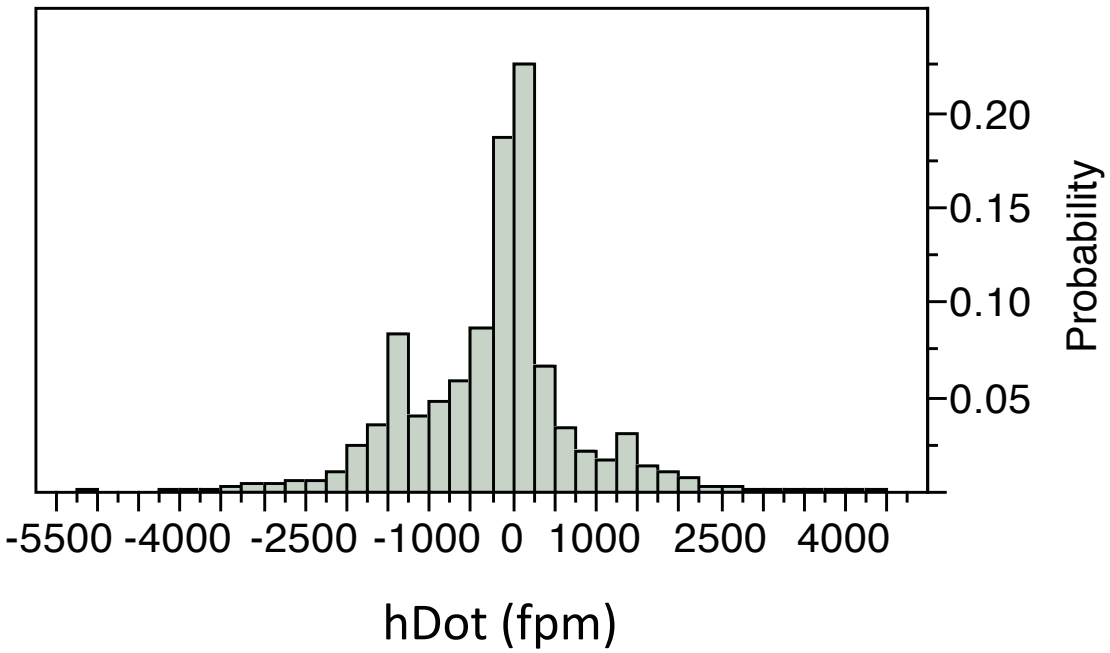
Quantiles

100.0%	max	4308
99.5%		2455.86
97.5%		1570.62
90.0%		741.701
75.0%	quartile	99
50.0%	median	-31
25.0%	quartile	-744
10.0%		-1438.7
2.5%		-2194.5
0.5%		-3023.7
0.0%	min	-6730

Summary Statistics

Mean	-246.0974
Std Dev	909.73485
Std Err Mean	11.742669
Upper 95% Mean	-223.0776
Lower 95% Mean	-269.1173
N	6002

hDot (vertical closure rate) – USAF



Quantiles

100.0%	max	4309
99.5%		2365.84
97.5%		1647.35
90.0%		737.699
75.0%	quartile	91.998
50.0%	median	-47
25.0%	quartile	-756.75
10.0%		-1442
2.5%		-2062.2
0.5%		-3095.9
0.0%	min	-5199

Summary Statistics

Mean	-251.3393
Std Dev	910.31886
Std Err Mean	12.13004
Upper 95% Mean	-227.5598
Lower 95% Mean	-275.1189
N	5632

IFR-VFR 500ft Altitude Separation – Well-Clear?

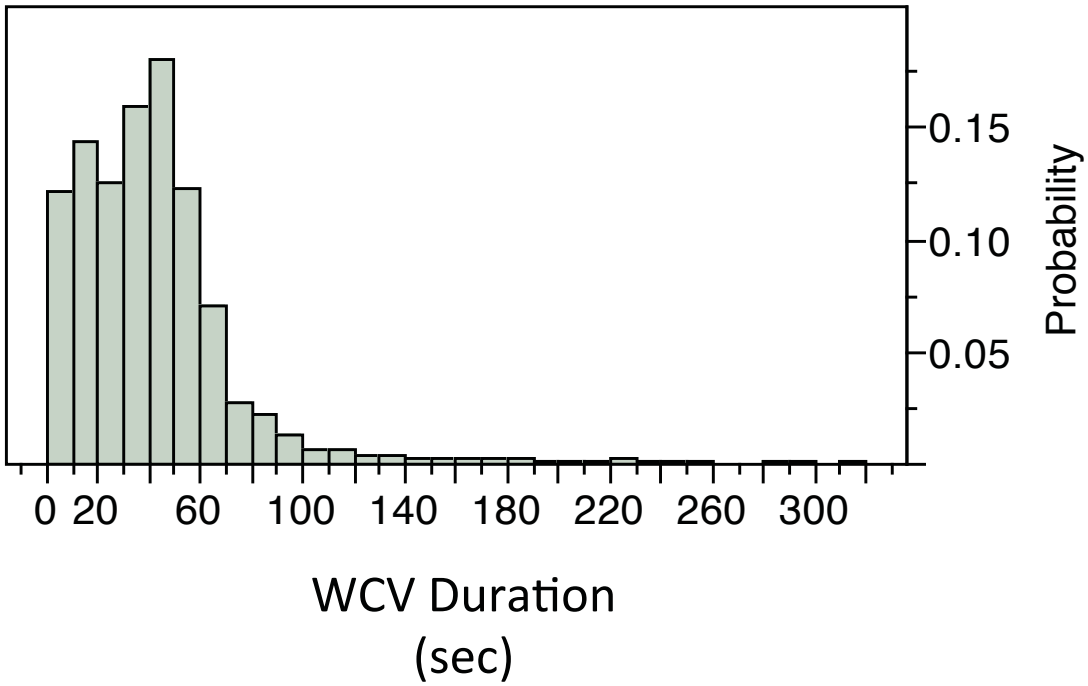
- MIT-LL uses 700 feet ZTHR
- NASA uses 475 feet ZTHR

Question: If two aircraft pass at 500ft and at level flight isn't that well-clear?

TCAS Sensitivity	Ownship Altitude (ft)	Percentage of WCVs that pass above 500ft
3	1,000-2,350	2.4%
4	2,350-5,000	4.1%
5	5,000-1,0000	3.4%
6	10,000-20,000	0.5%
Total	-	10.5%

Magnitude of MIT-LL that pass above 500ft and vertical closure rate is less than 100 FPM (level).

WCV Duration – NASA



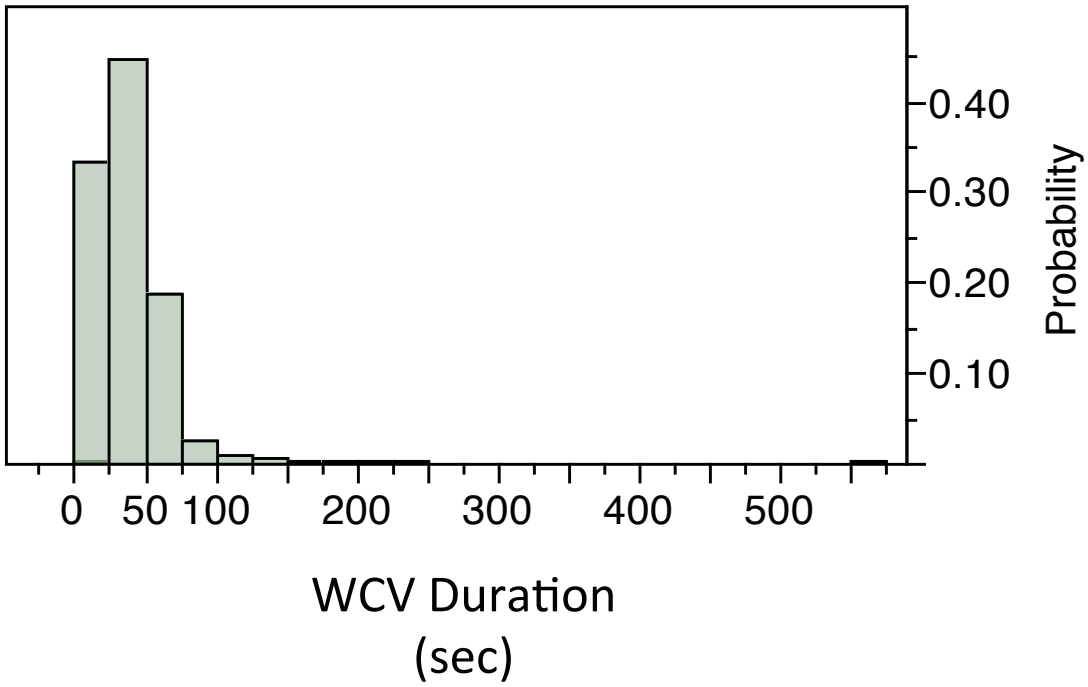
Quantiles

100.0%	max	314
99.5%		169.26
97.5%		100
90.0%		66
75.0%	quartile	50
50.0%	median	36
25.0%	quartile	18
10.0%		8
2.5%		2
0.5%		2
0.0%	min	2

Summary Statistics

Mean	38.042021
Std Dev	27.380679
Std Err Mean	0.3403231
Upper 95% Mean	38.709166
Lower 95% Mean	37.374875
N	6473

WCV Duration – MIT-LL



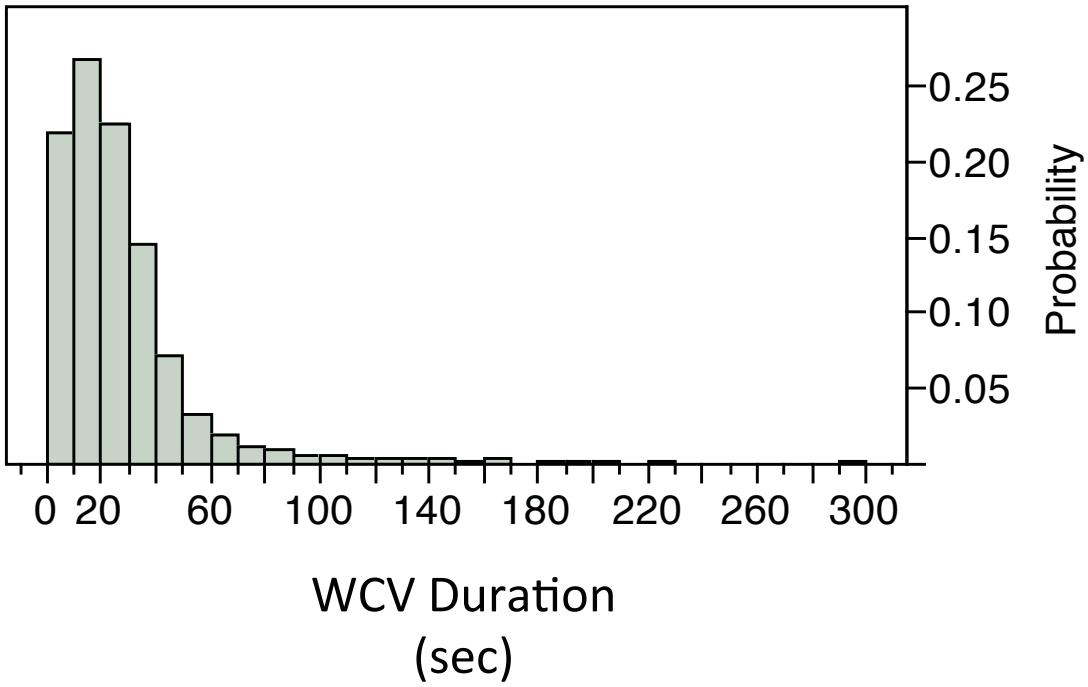
Quantiles

100.0%	max	552
99.5%		141.97
97.5%		87.85
90.0%		58
75.0%	quartile	48
50.0%	median	38
25.0%	quartile	18
10.0%		8
2.5%		2
0.5%		2
0.0%	min	2

Summary Statistics

Mean	36.176608
Std Dev	24.139063
Std Err Mean	0.311582
Upper 95% Mean	36.787421
Lower 95% Mean	35.565795
N	6002

WCV Duration – USAF



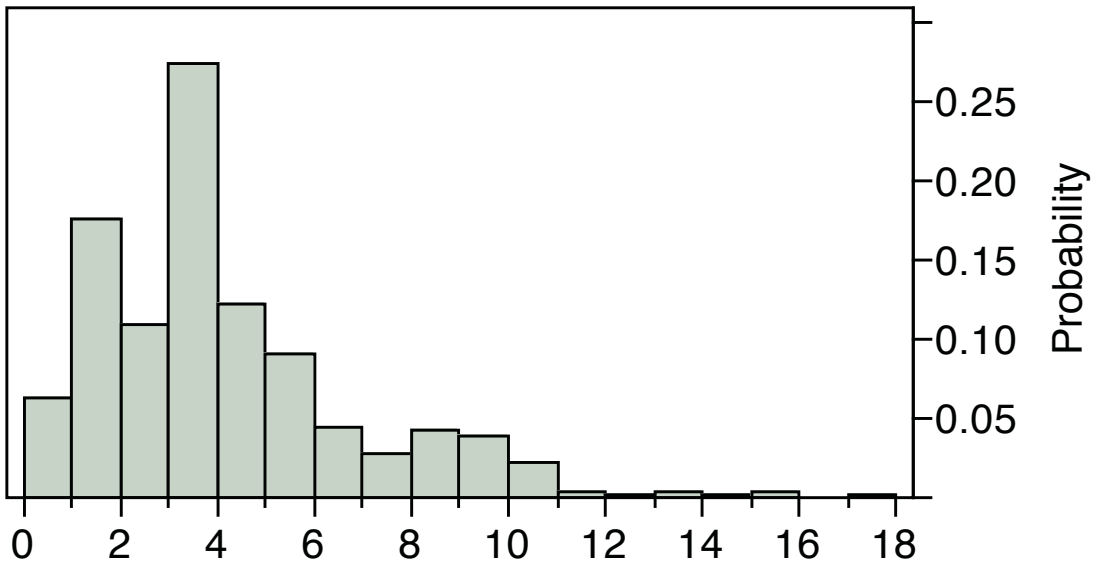
Quantiles

100.0%	max	298
99.5%		131.67
97.5%		76.35
90.0%		44
75.0%	quartile	32
50.0%	median	20
25.0%	quartile	10
10.0%		4
2.5%		2
0.5%		2
0.0%	min	2

Summary Statistics

Mean	23.896662
Std Dev	20.776644
Std Err Mean	0.2768497
Upper 95% Mean	24.439394
Lower 95% Mean	23.35393
N	5632

Ownship Altitude at WCV – NASA



Ownship Altitude at WCV
(10^3 * feet)

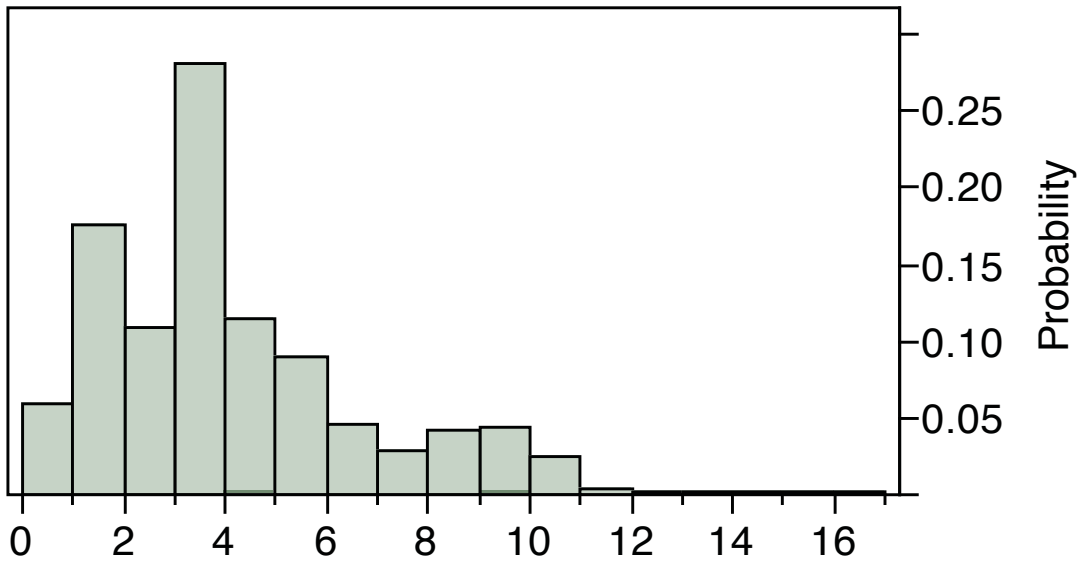
Quantiles

100.0%	max	17
99.5%		10.8118
97.5%		10
90.0%		8
75.0%	quartile	5
50.0%	median	3.44
25.0%	quartile	2.1085
10.0%		1.2882
2.5%		0.82985
0.5%		0.759
0.0%	min	0.75

Summary Statistics

Mean	3.9361542
Std Dev	2.3863824
Std Err Mean	0.0296611
Upper 95% Mean	3.9942997
Lower 95% Mean	3.8780086
N	6473

Ownship Altitude at WCV – MIT-LL



Ownship Altitude at WCV
(10^3 * feet)

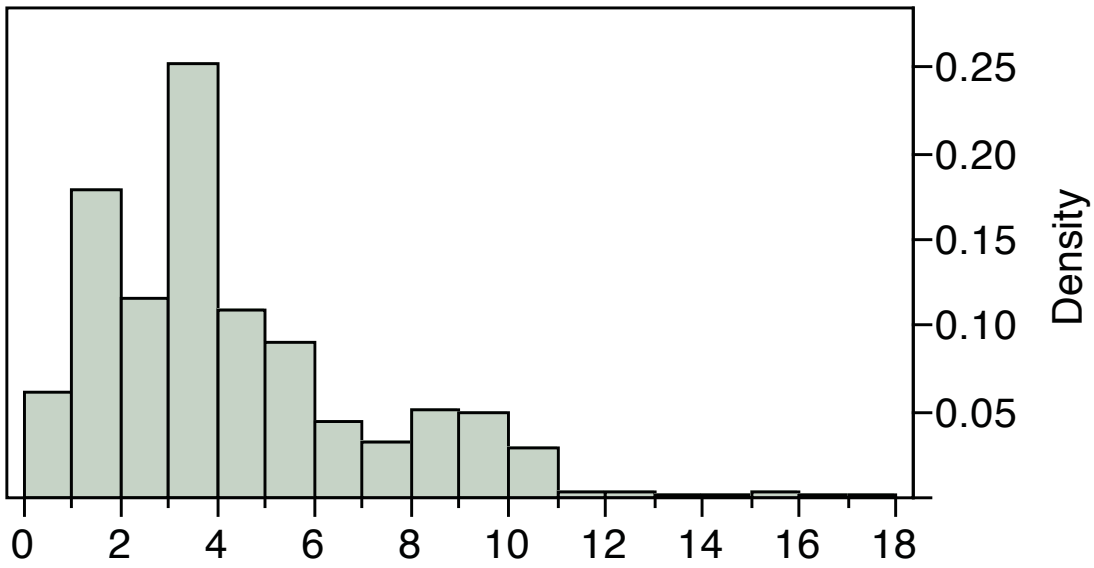
Quantiles

100.0%	max	16.191
99.5%		10.5522
97.5%		10
90.0%		8
75.0%	quartile	5
50.0%	median	3.471
25.0%	quartile	2.14875
10.0%		1.321
2.5%		0.83
0.5%		0.761
0.0%	min	0.752

Summary Statistics

Mean	3.9732962
Std Dev	2.407336
Std Err Mean	0.0310734
Upper 95% Mean	4.0342113
Lower 95% Mean	3.9123812
N	6002

Ownship Altitude at WCV – USAF



Ownship Altitude at WCV
(10^3 * feet)

Quantiles

100.0%	max	17
99.5%		11.7964
97.5%		10
90.0%		8
75.0%	quartile	5.12825
50.0%	median	3.464
25.0%	quartile	2.097
10.0%		1.291
2.5%		0.828
0.5%		0.76017
0.0%	min	0.752

Summary Statistics

Mean	4.0715243
Std Dev	2.5496832
Std Err Mean	0.0339746
Upper 95% Mean	4.1381277
Lower 95% Mean	4.0049209
N	5632

Conclusion

- Tomorrow I will dig deeper in results for the SARP accepted metrics
- P(NMAC|WCV) is in the ball-park of the tuned 1.5%
- For all UAS mission types each WC definition has similar performance
- TCAS Sensitivity level between 10,000-20,000 feet shows high P(TCAS-RA|WCV) for all WC definitions
- Doesn't look like TCOA really captures many encounters given LL encounter model and ACES UAS vs. VFR encounters

ACES Unmitigated (and Some Mitigated) Results Supporting Selection of SARP Well-Clear Definition

Confesor Santiago

8/5/14 – 8/7/14

Supported by Marcus Johnson, Doug Isaacson, and David Hershey

TCAS Model Summary

- As a proxy for whether a TCAS Corrective RA would be presented we use model published by NASA Langley in GNC 2013 paper
- Given UAV encounter, TCAS RA model is computed from standpoint of the intruder (assumed TCAS equipped)
- At every cycle as intruder encounters UAV, we compute if Equation (12) and Equation (14) are true, then its marked as a TCAS RA
- Mathematical model is the same as the one used by NASA and MIT-LL for well-clear definition (modTau and time to co-alt)
- However, altitude dependent thresholds are used based on intruder's own altitude
- Also, there is a single tau threshold (for SARP we decoupled modTau and time-to-co-altitude)

TCAS RA Model Altitude Dependent Thresholds

Own Altitude (ft)	SL	Tau (sec)	DMOD (nmi)	ZTHR (ft)	ALIM (ft)	HMD (ft)
1000 - 2350	3	15	0.20	600	300	1215
2350 - 5000	4	20	0.35	600	300	2126
5000 - 10000	5	25	0.55	600	350	3342
10000 - 20000	6	30	0.80	600	400	4861
20000 - 42000	7	35	1.10	700	600	6683
> 42000	7	35	1.10	800	700	6683

Intruder Altitude: 2,000 ft – 17,999ft

** Source: "A TCAS-II RESOLUTION ADVISORY DETECTION ALGORITHM," Cesar Muñoz, Anthony Narkawicz, and James Chamberlain, AIAA Guidance, Navigation, and Control Conference, 2013. Table 1: TCAS Sensitivity Level Definition and Alarm Thresholds for RAs*

TCAS RA Model

```
[( r <= DMOD) or
      ((0 <= tau_mod <= tau_thresh) and
      (HMD <= HMD_thresh))]

      and


[(h <= ZTHR) or
      (0 <= vert_tau <= tau_thresh)]
```

Preventive: `vertDistCPA >= ALIM`

Corrective: `vertDistCPA < ALIM`

P(TCAS-RA|WCV) Unmitigated ACES Result

Probability of Well-Clear Violation (WCV) with TCAS RA prior to WCV

- Assumption: Intruders (manned) experiencing TCAS-RA's while UAS DAA system detects it as well-clear is undesirable.
- The smaller the better
- $$\frac{\text{Number of WCVs with TCAS-RA prior to WCV}}{\text{Total Number of WCVs}}$$
- To measure TCAS RA used data from 2 seconds prior to WCV

TCAS-RA Rates Mitigated Result

- While detecting and resolving for WCVs (mitigated), at what rate do we trigger a TCAS-RA?
  - Didn't have time for break-out of Corr-RA and Prev-RA

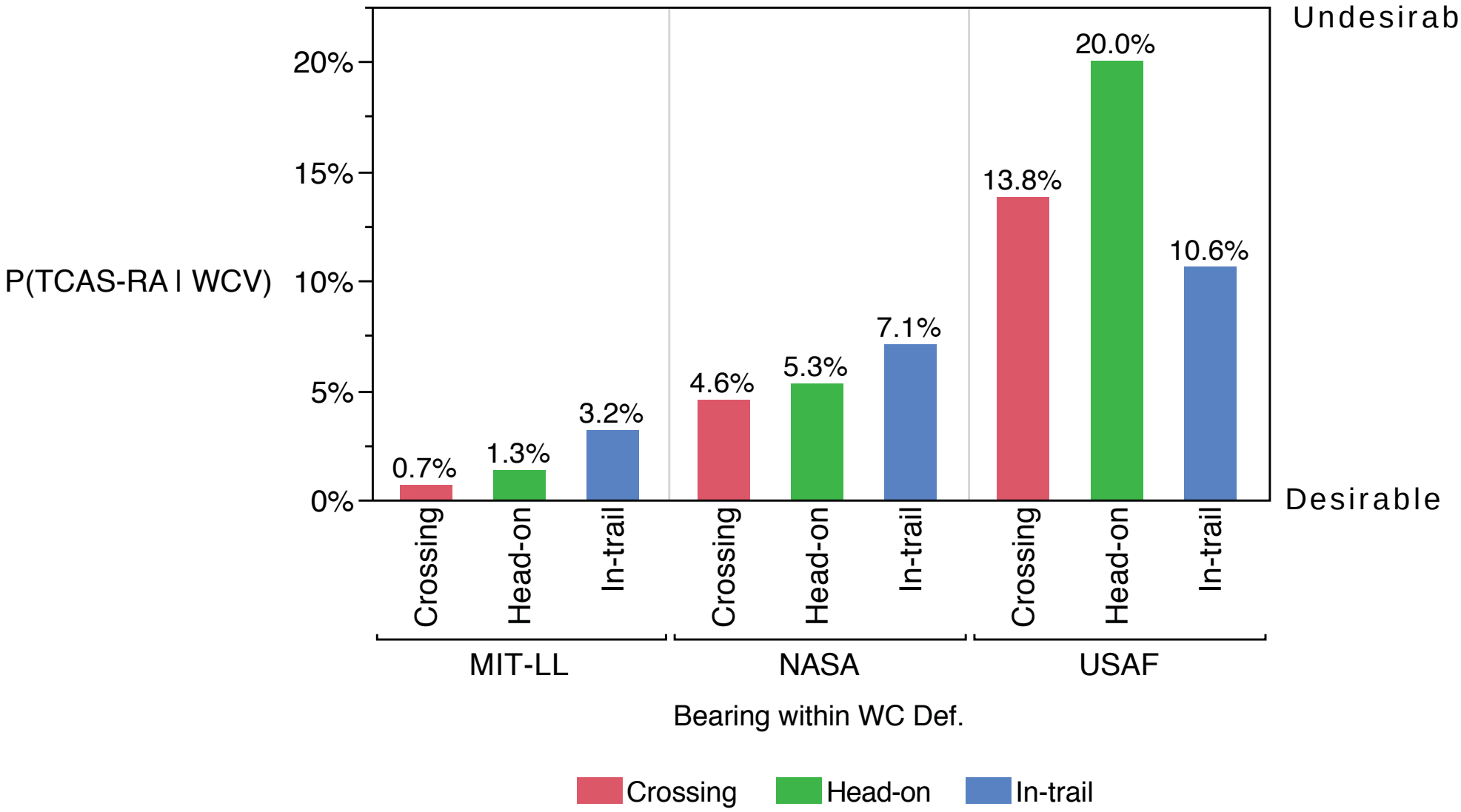
$$\frac{\text{\# of TCAS-RA's}}{\text{Total UAS Flight Hour}}$$

P(TCAS-RA|WCV) Unmitigated ACES Result

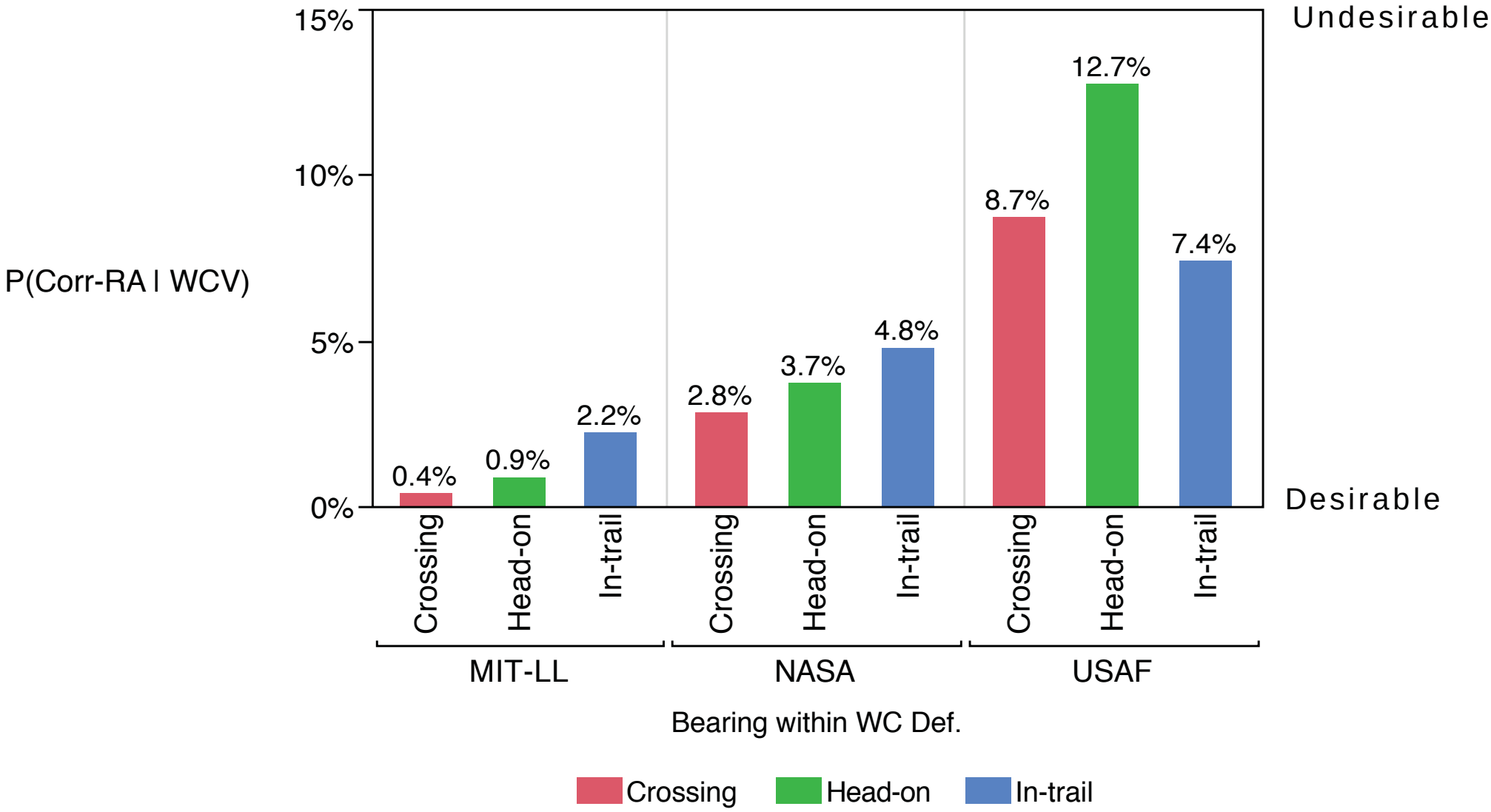
WC Definition	No. of Corrective RAs	No. of Preventive RAs	No. of Total RAs
MIT-LL	50	27	77
NASA	224	114	338
USAF	551	308	839

Total TCAS-RA Counts for all 8 days simulated

P(TCAS-RA|WCV) Unmitigated ACES Result

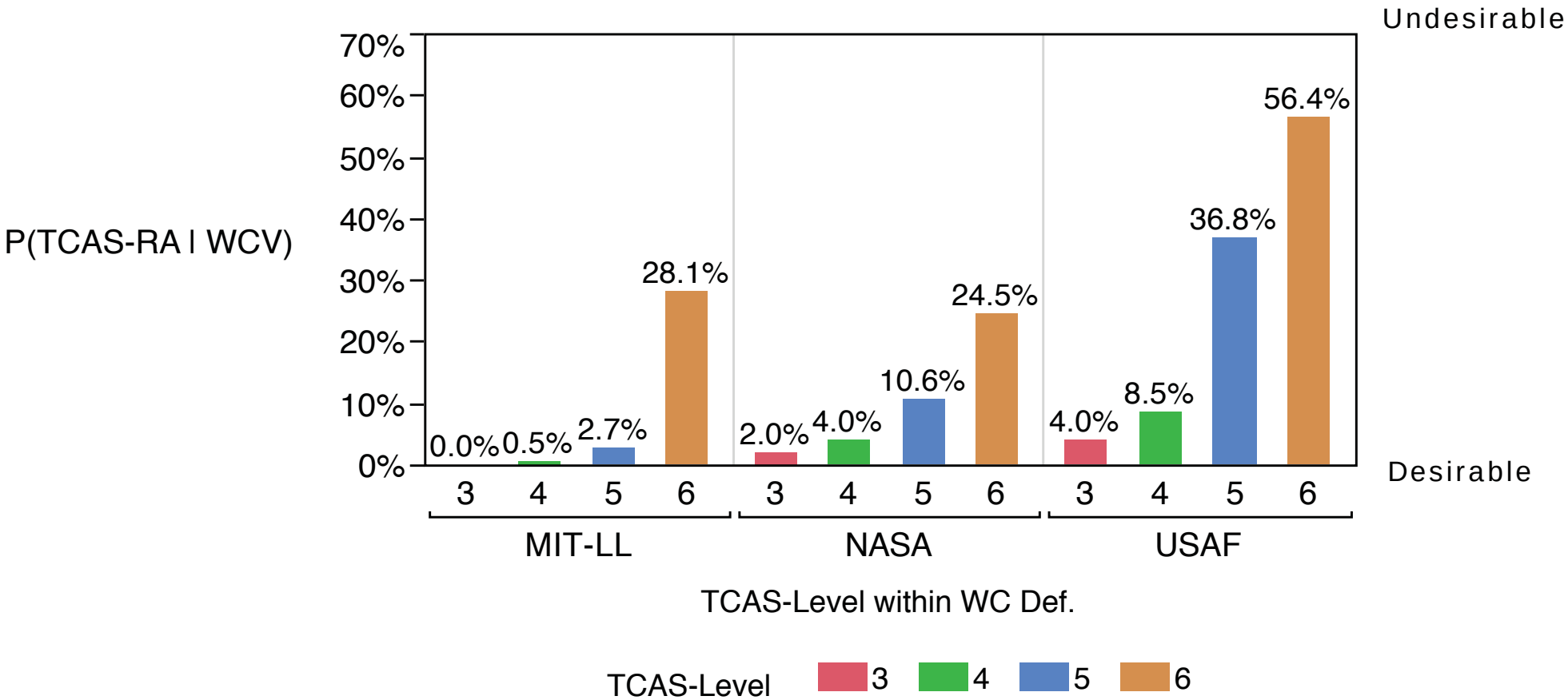


P(Corr-RA|WCV) Unmitigated ACES Result



P(TCAS-RA|WCV) Unmitigated ACES Result

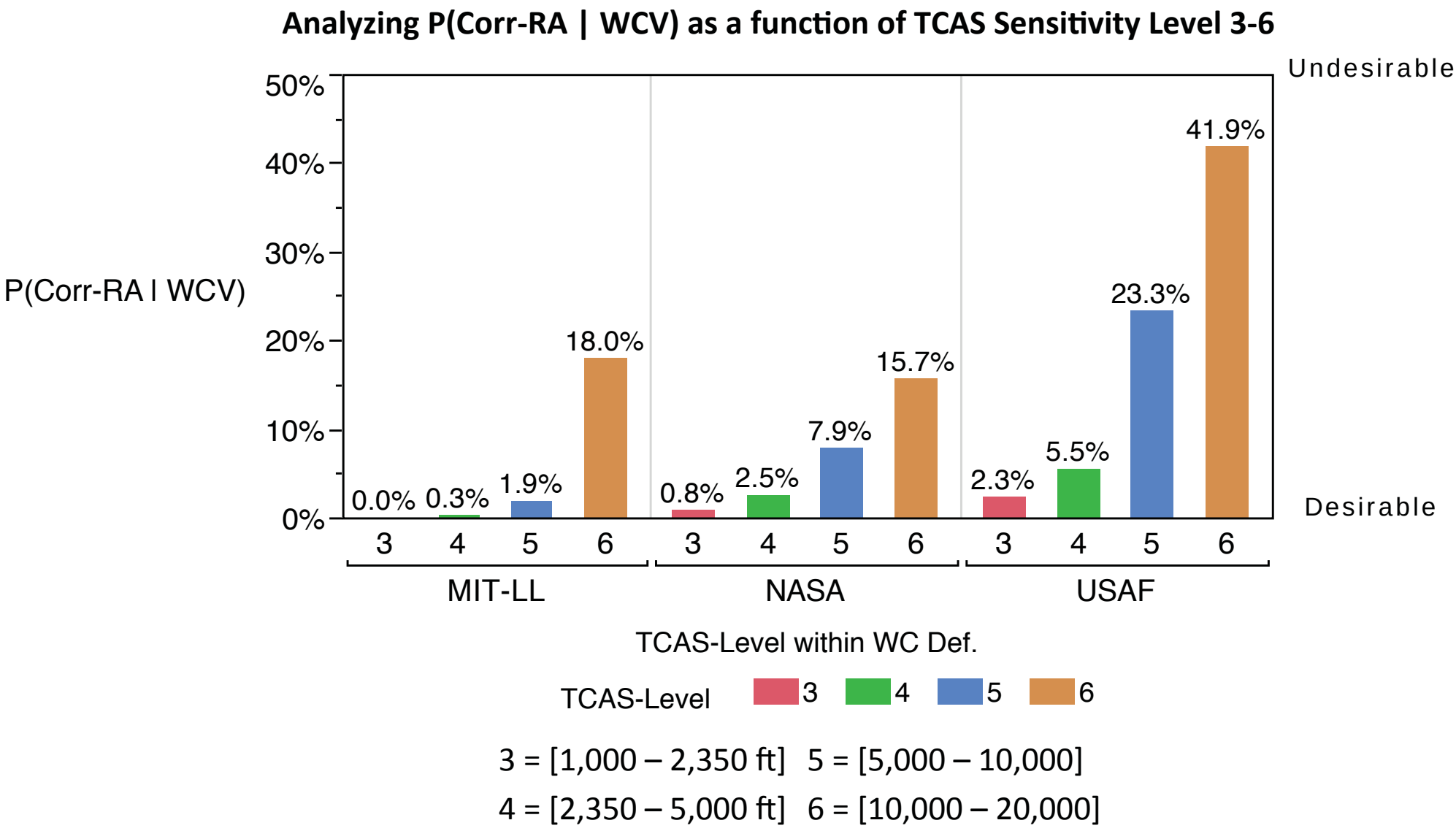
Analyzing P(TCAS-RA | WCV) as a function of TCAS Sensitivity Level 3-6



3 = [1,000 – 2,350 ft] 5 = [5,000 – 10,000]

4 = [2,350 – 5,000 ft] 6 = [10,000 – 20,000]

P(Corr-RA|WCV) Unmitigated ACES Result



3 = [1,000 – 2,350 ft] 5 = [5,000 – 10,000]

4 = [2,350 – 5,000 ft] 6 = [10,000 – 20,000]

P(TCAS-RA|WCV) Unmitigated ACES Result

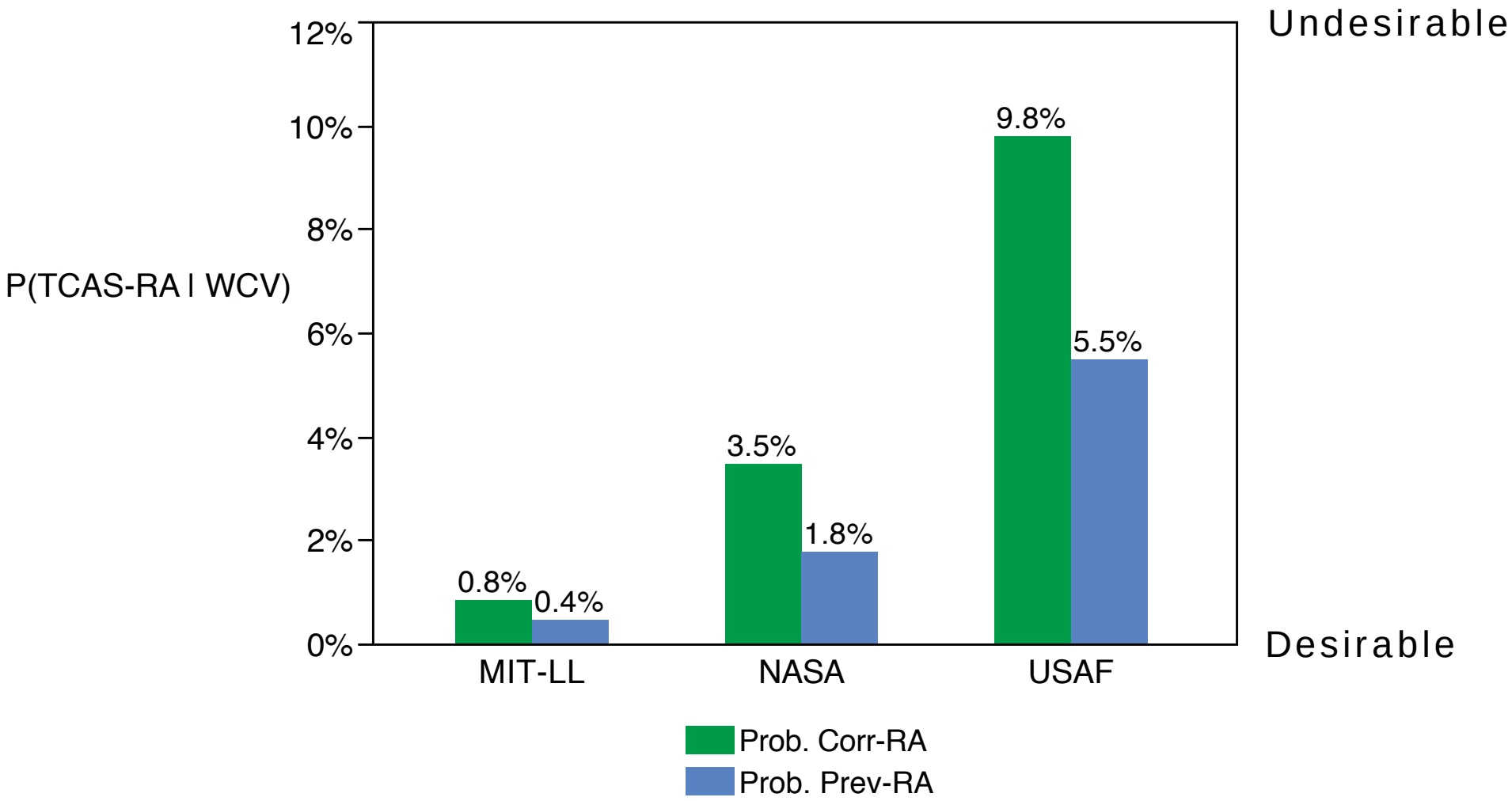
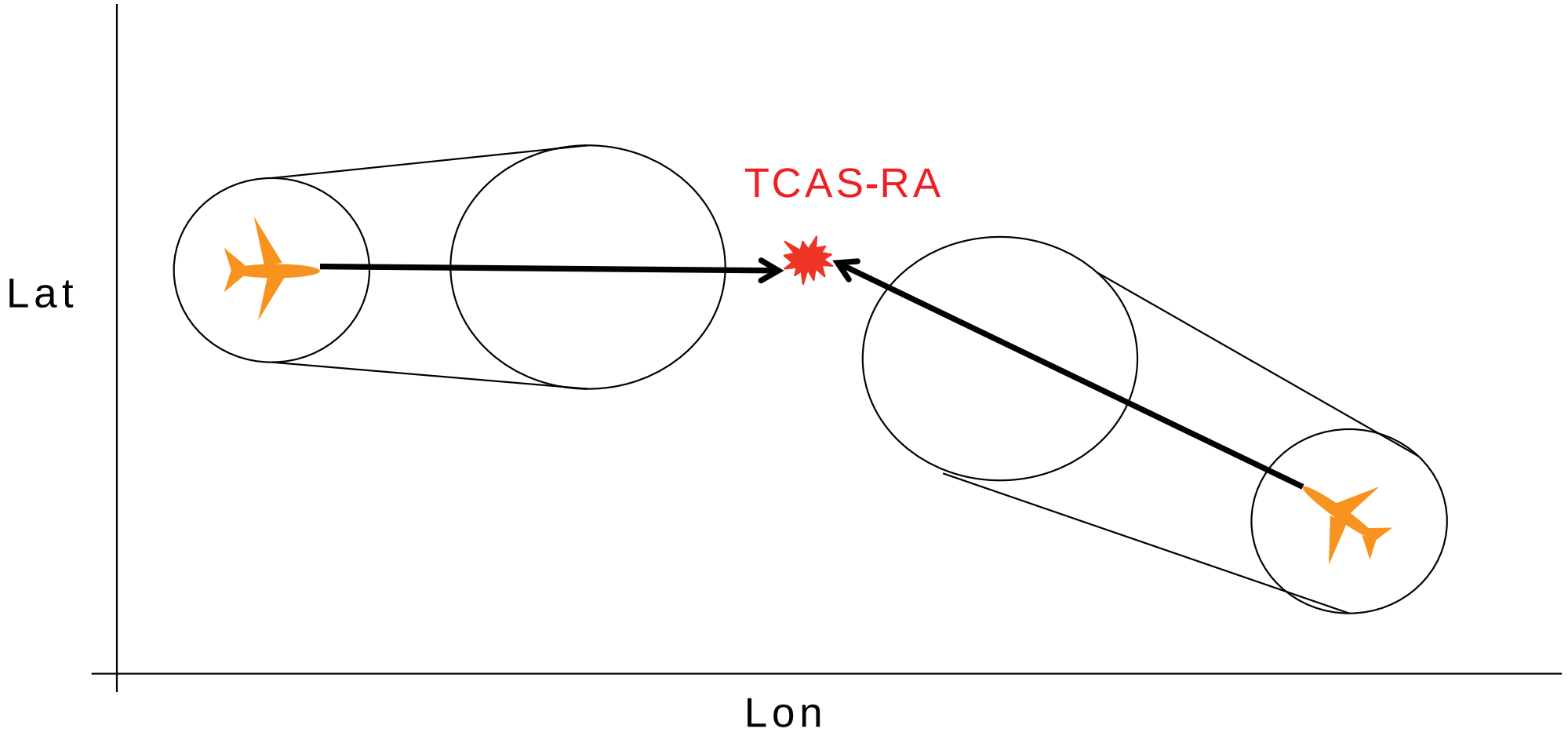


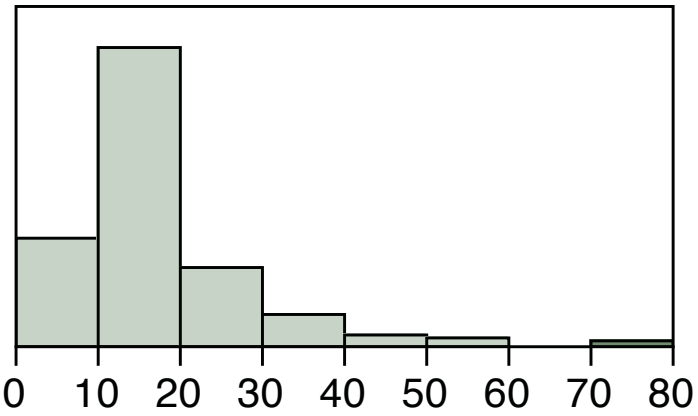
Illustration of Typical USAF Case with TCAS-RA



- A lot of the time, TCAS-RA model, which is based on modTau, triggers farther out than the length of the horizontal cone for head-on and crossing encounters
- More of an issue in the modTau, rather than the Z_THR

NASA vs. MIT-LL Unmitigated TCAS-RA Comparison

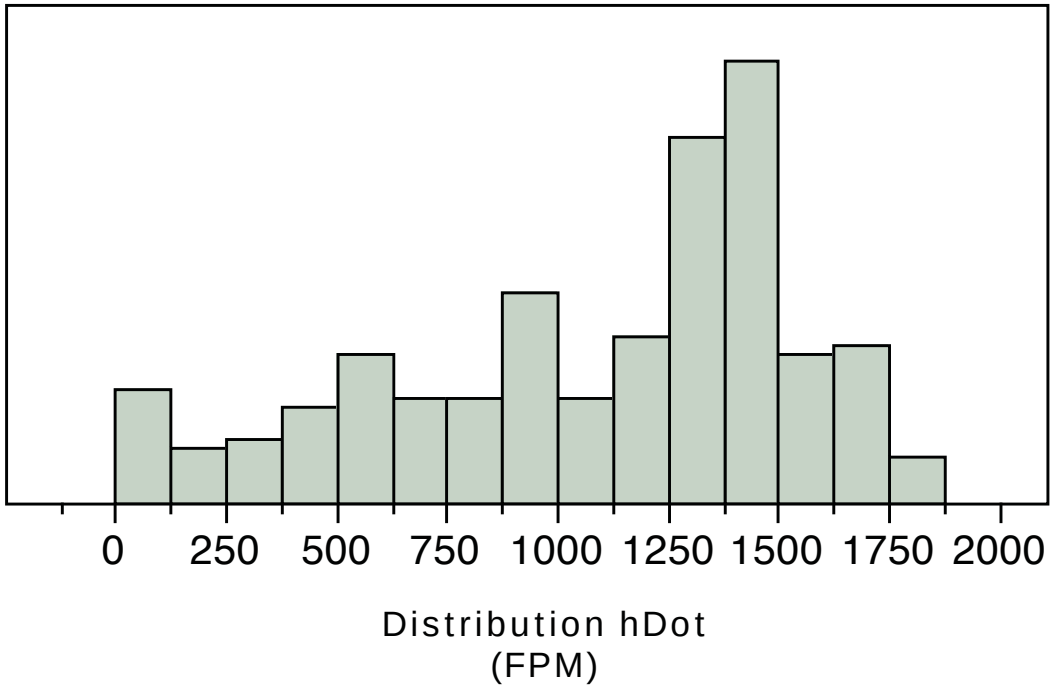
- Identified 266 NASA WCVs where:
  - An associated MIT-LL WCV occurred with same encounter pair
  - Altitudes at WCV are within 300 feet of MIT-LL
  - TCAS-RA occurred prior to time of NASA WCV
  - TCAS-RA occurred after MIT-LL WCVs
- These cases are the majority of why P(TCAS-RA |WCV) is higher for NASA WC definition.



Distribution of (NASA WCV Time – MIT-LL WCV Time) seconds

Stat	Value (sec)
Mean	14.9
Std Dev	9.8
Median	10
Min	2
Max	76
N	266

NASA vs. MIT-LL Unmitigated TCAS-RA Comparison

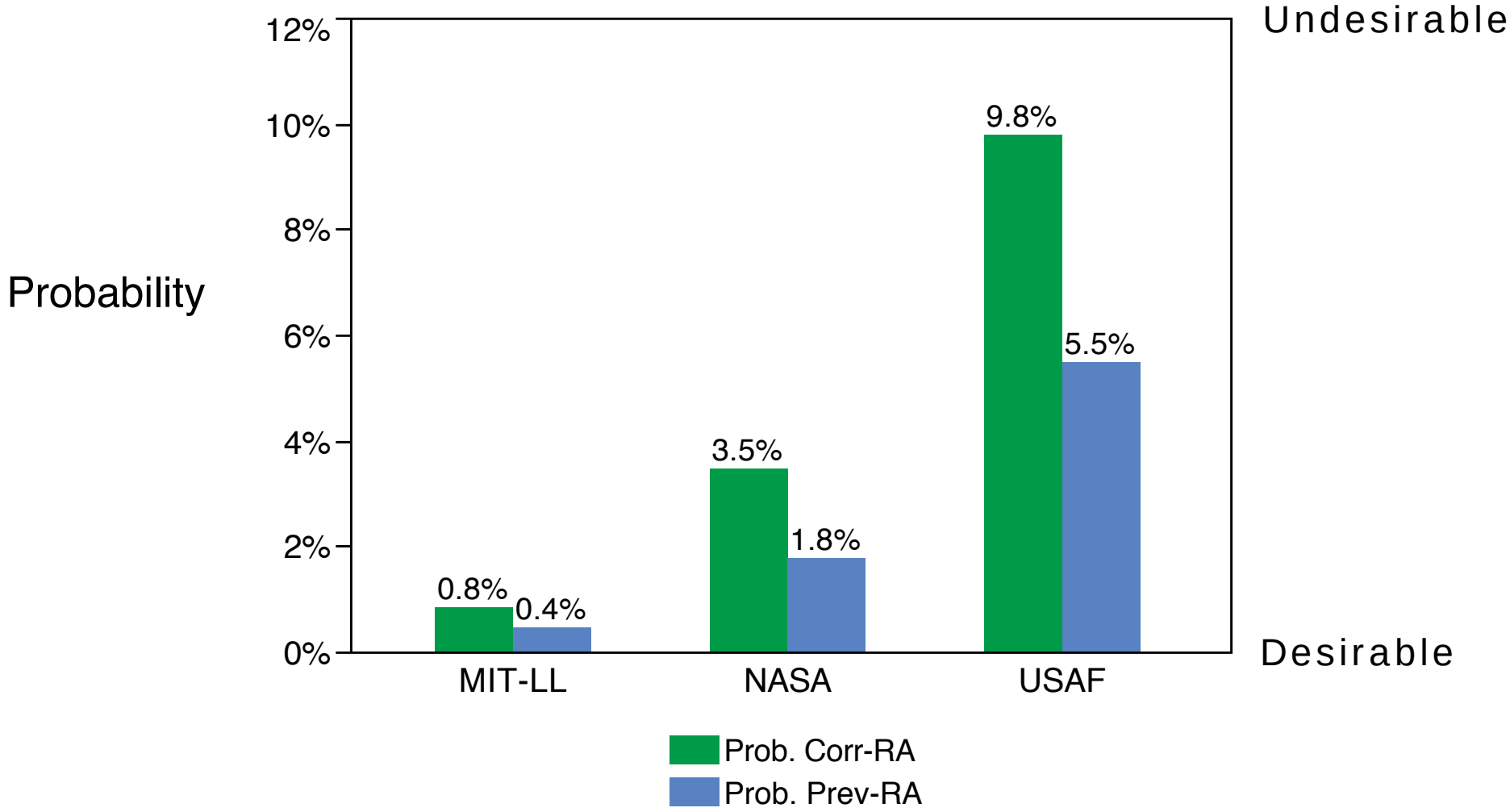


Stat	Value (fpm)
Mean	1084.8
Std Dev	469.5
Median	1253
Min	0
Max	1873
N	266

- At the lower vertical closure rates (hDot), MIT-LL's 700 feet ZTHR protects against TCAS-RA at 600 feet
- 97.5% of the WCVs occur below 10,000ft; TCAS uses at 25 tau threshold there
- In case of larger vertical closure rates, TCOA of 20 is within TCAS limits, hence TCAS-RA occurring prior to WCV
- MIT-LL's 700 feet Z_THR equates to ~33.5 seconds TCOA for median hDot = 1253 fpm, which is outside TCAS's 25 tau threshold, and ~29 seconds TCOA for TCAS-RA model

P(TCAS-RA|WCV) Unmitigated ACES Result

Final Result



TCAS-RA Rate Mitigated

- NASA: 3.9 x 10^{-3} RA/flt-hour (filtered out anomaly WCVs)
- MIT-LL: 8.47 x 10^{-4} RA/flt-hour (filtered out anomaly WCVs)
- USAF: 1.52 x 10^{-2} RA/flt-hour (filtered out anomaly WCVs)

WCV Rate Unmitigated and WCV/Encounter Rate Mitigated ACES Result

WCV Rate Unmitigated ACES Result

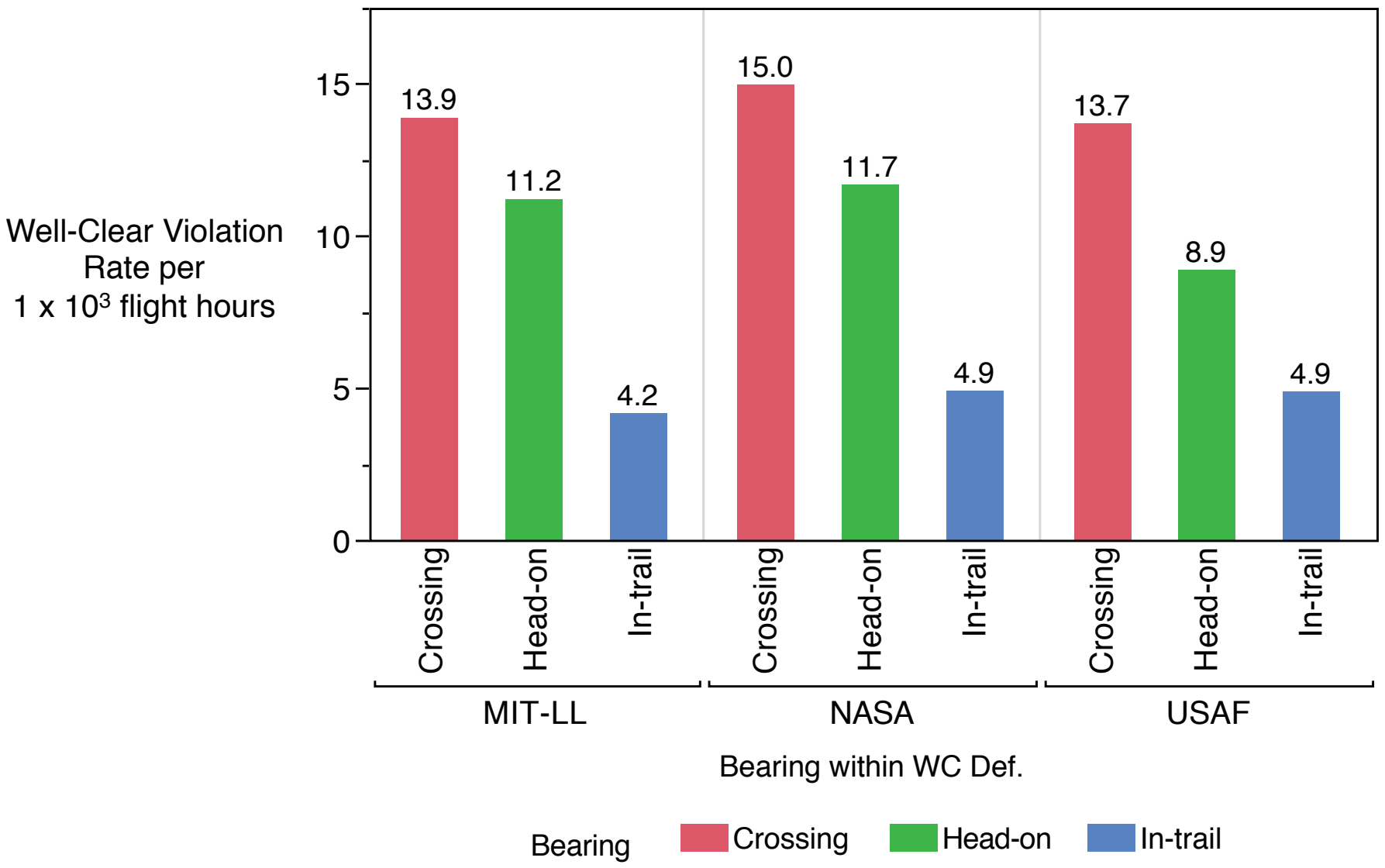
Well-Clear Volume Penetration Rate per Flight Hour

- Intuition tells me the lower the rate the better.
- The complement is interesting, because the higher the rate points to presumably that the well-clear definition is larger, which may make the system safe, however may have negative affect on interoperability to ATC.
- There is a tradeoff here…

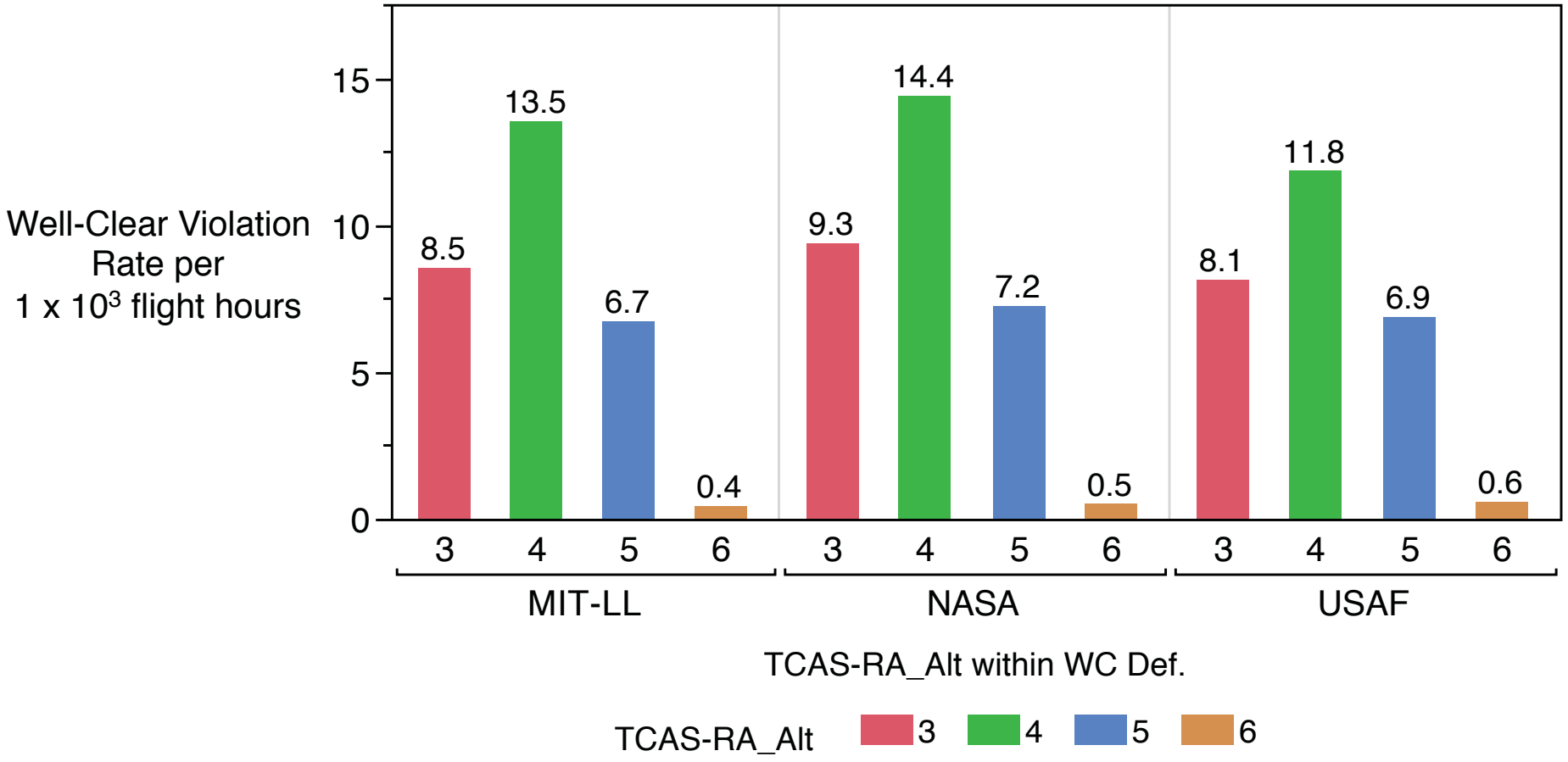
$$\frac{\text{Number of WCVs}}{\text{Number of flight hours}}$$

$$\frac{\text{Number of SST Encounters where Maneuver is Required}}{\text{Number of flight hours}}$$

WCV Rate Unmitigated ACES Result



WCV Rate Unmitigated ACES Result



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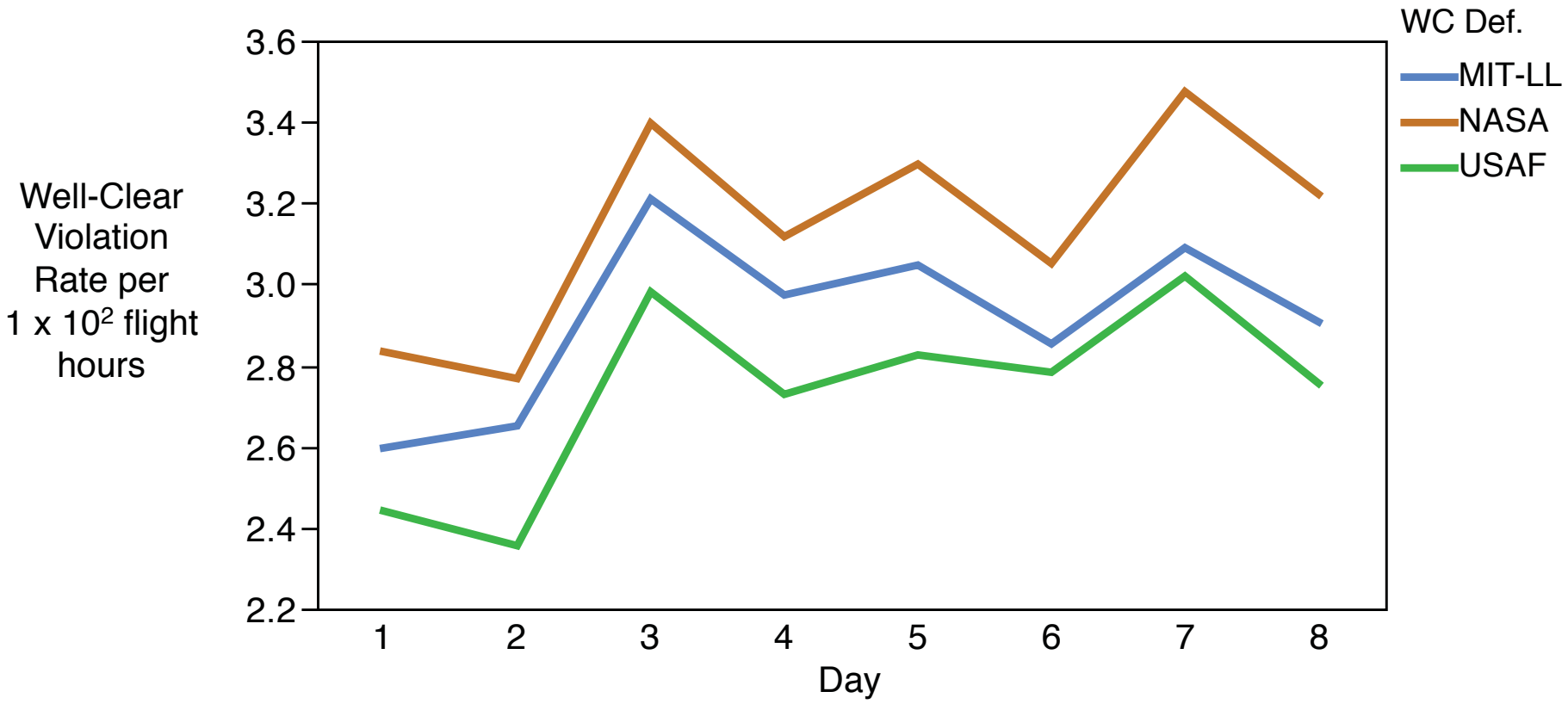
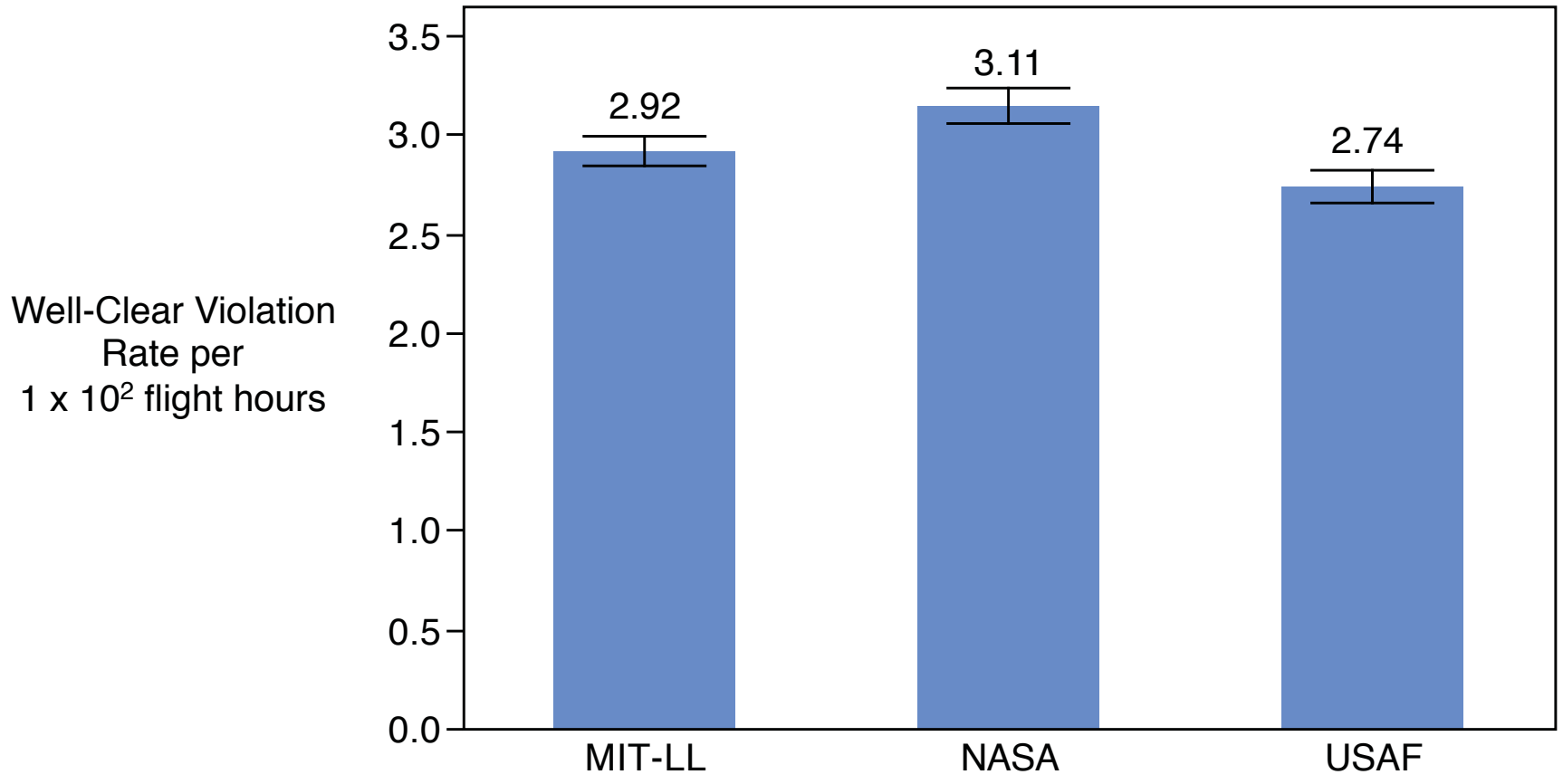
4 = [2,350 – 5,000 ft] 6 = [10,000 – 20,000 ft]

WCV Rate Unmitigated ACES Result



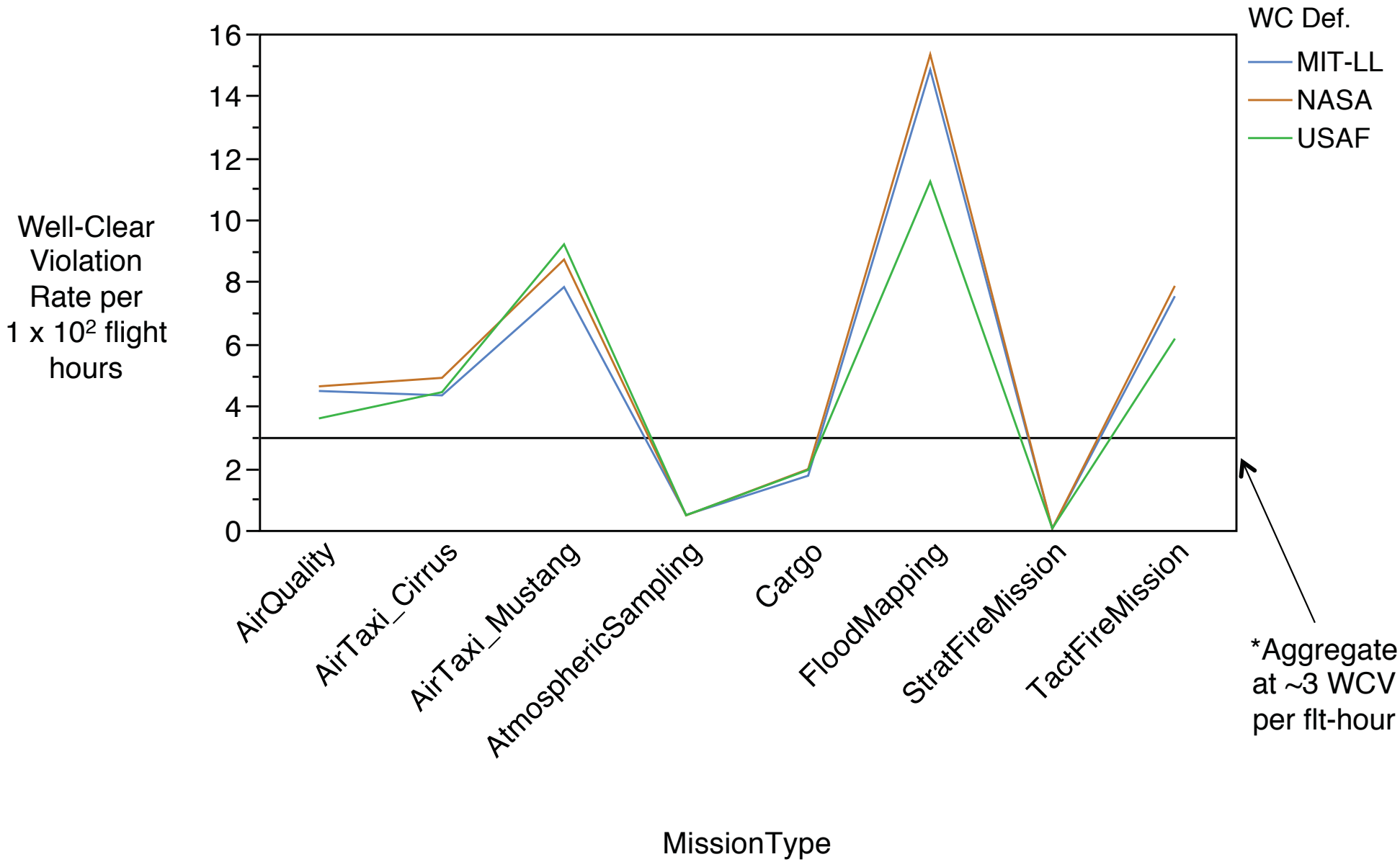
WCV Rate reveals similar trends within each day for each WC definition.

WCV Rate Unmitigated ACES Result

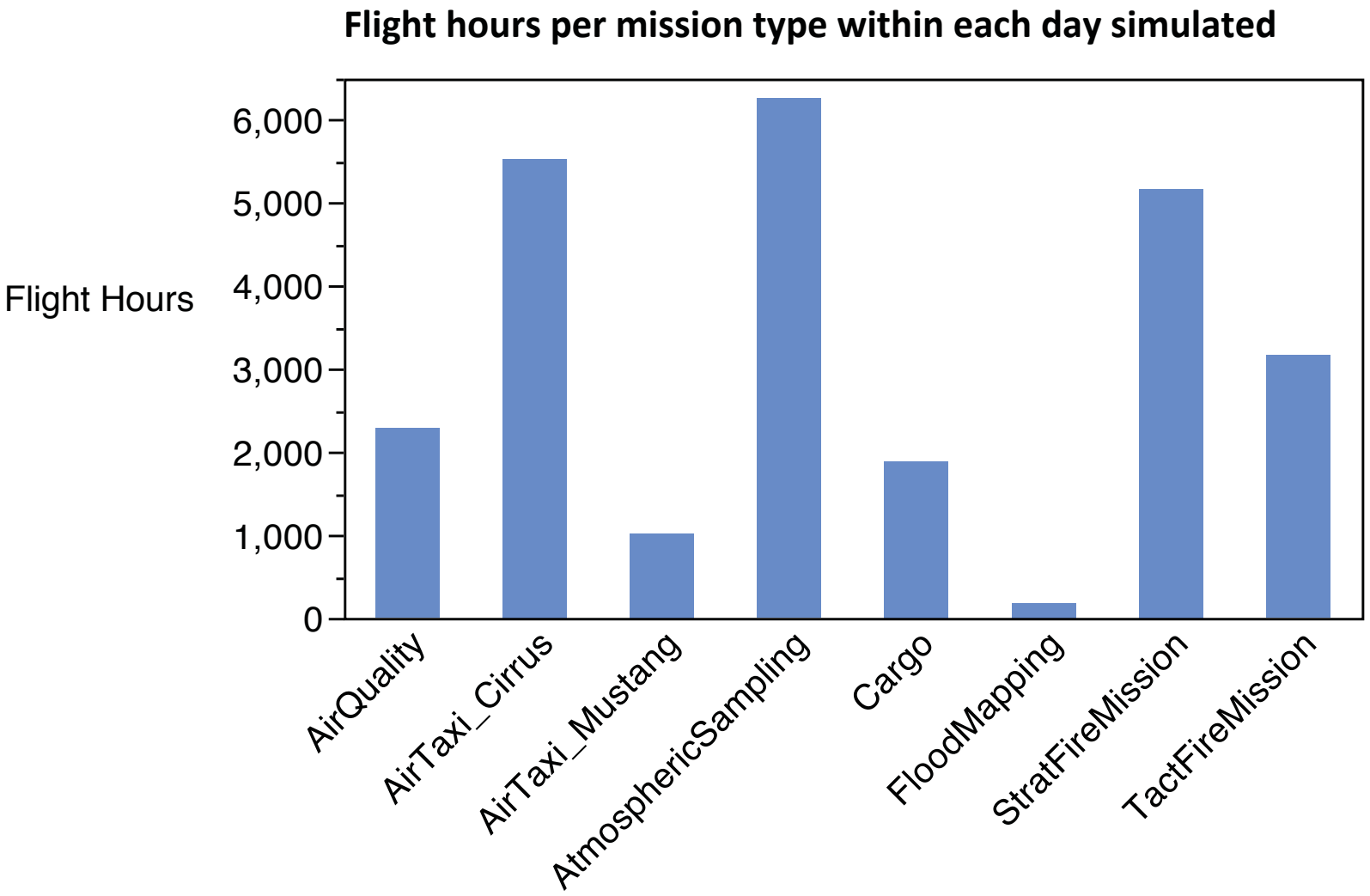


WCV Rate reveals similar trends within each day for each WC definition.

WCV Rate Unmitigated ACES Result

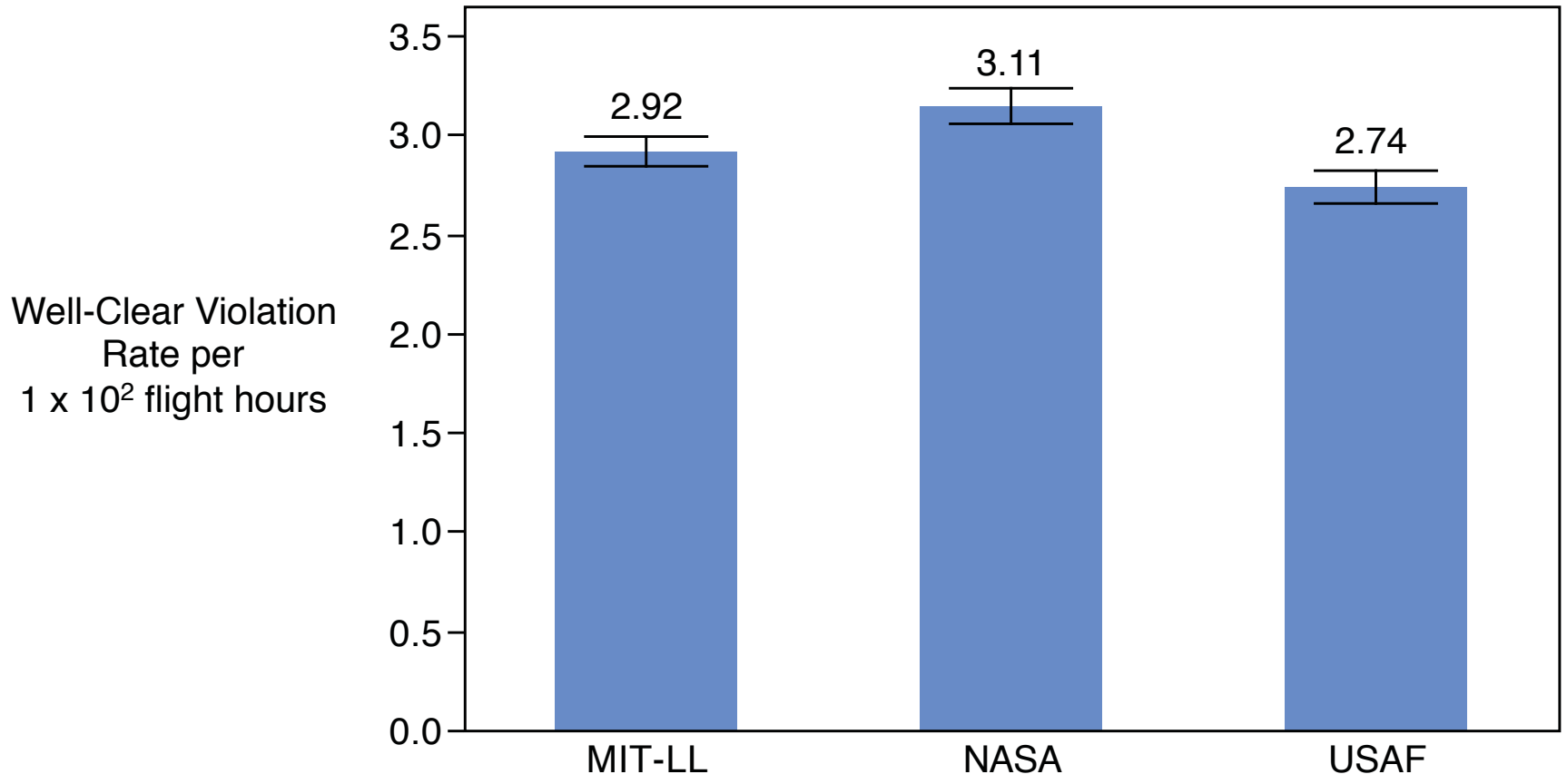


WCV Rate Unmitigated ACES Result



WCV Rate Unmitigated ACES Result

Final Result



WCV Rate reveals similar trends within each day for each WC definition.

WCV Rate Mitigated ACES Result

Final Result

WCD	WCV_rate (flt-hours)	SST_rate (flt-hours)*
NASA	1.97×10^3	1.30×10^1
MIT-LL	1.55×10^3	1.05×10^1
USAF	5.60×10^3	1.76×10^1

* SST_rate is the rate in which mitigation was needed, i.e. crossing SST

- For all WC definitions mitigation was able to reduce WCV rate by an order of magnitude (100s of flt-hours to 1000s flt-hours)
- Similar to WCV rate in unmitigated, the rate of "requiring" self-separation maneuver is about the same
- NASA and MIT-LL in ballpark, USAF is a couple multiples larger

Miss Distances at CPA
and
Minimum Time Until NMAC from WCV

Unmitigated ACES Result

Miss Distances at CPA

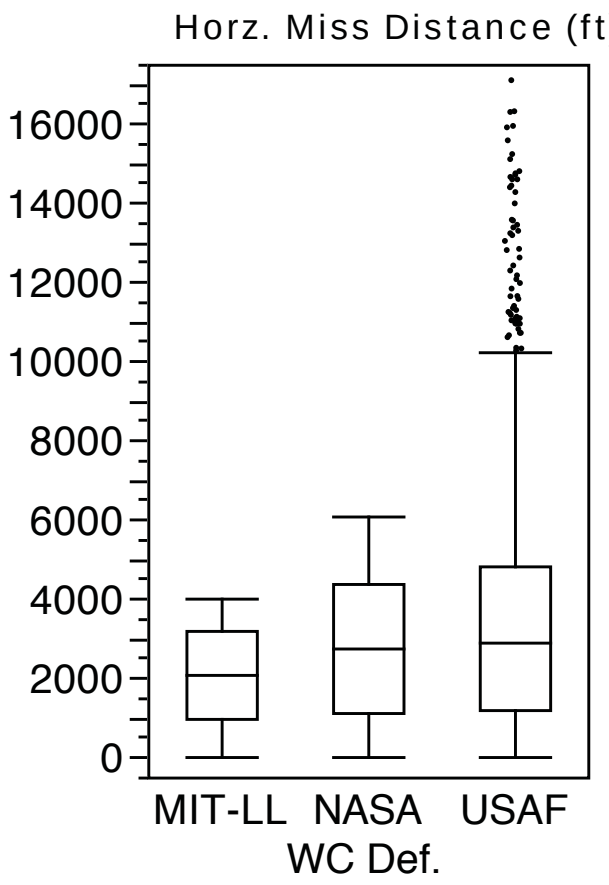
- Intuition tells me the higher the miss distances the better.
- Although, based on unmitigated encounters only, miss distances may not be a good indicator of WC definition performance.
- Two definitions of CPA:
  - Minimum slant range between ownship and intruder
  - Minimum slant range normalized for NMAC 500ft hSep and 100ft vSep (5-to-1 ratio)

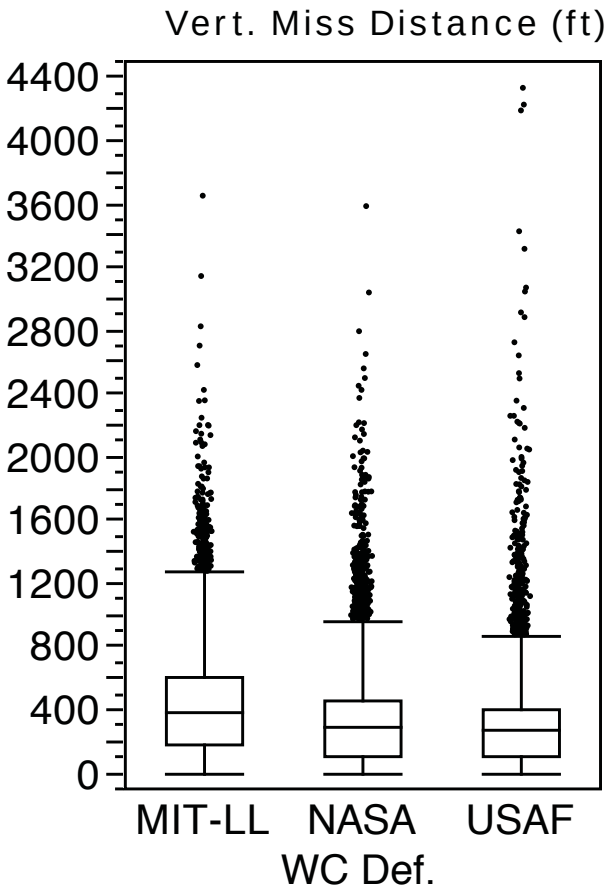
Minimum Time Until NMAC from WCV

- Intuition tells me the higher the minimum time until NMAC the better.
- In other words, the more time between becoming a WCV to becoming NMAC the "safer".
- Since the unmitigated P(NMAC|WCV) and WCV rate is about the same, this is a way to analyze that not every WCV is created equal. Which definition is generally closer to an NMAC.
- Not only is minimum shown, but also the distribution.

Min (NMAC_time – WCV_time)

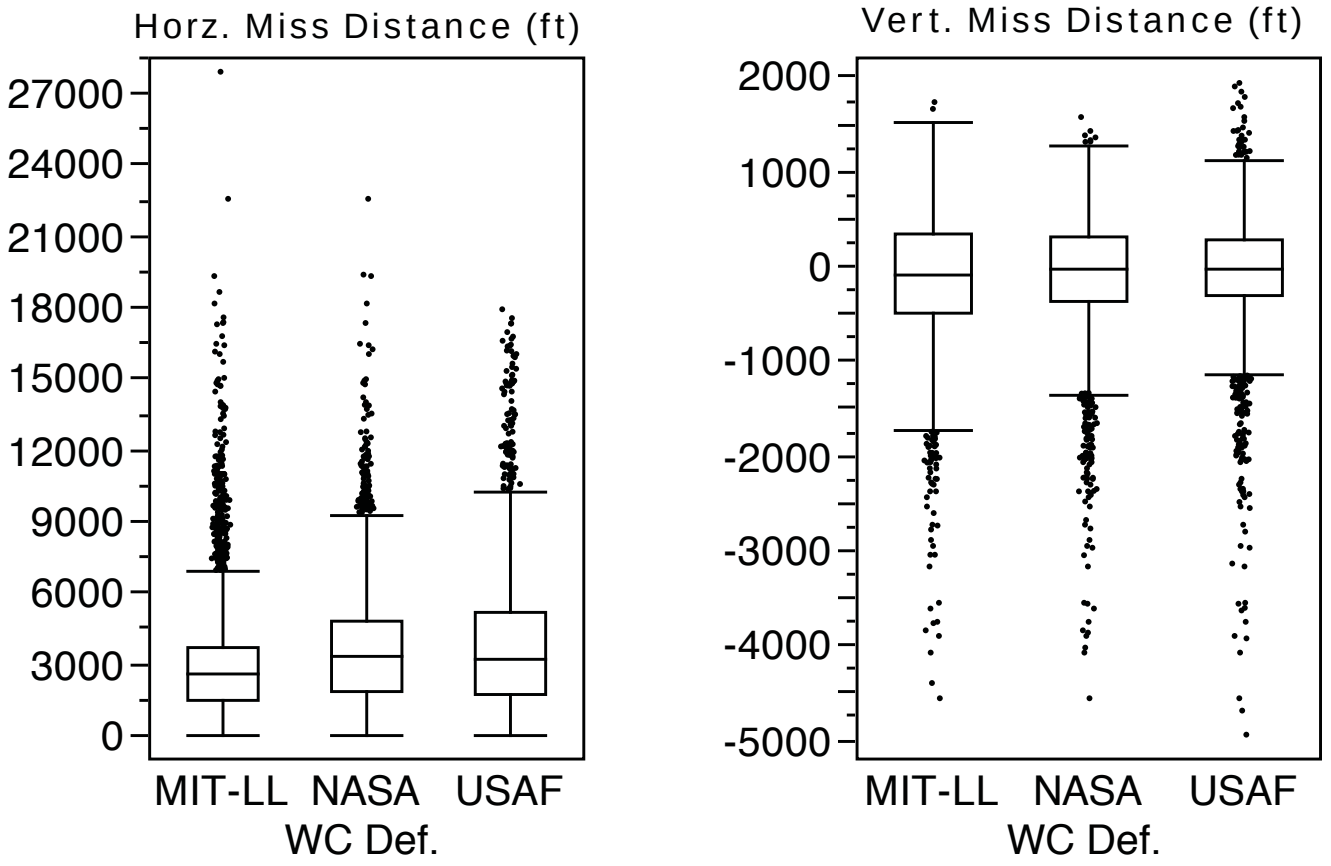
Predicted Min. Slant Range CPA - Miss Distances





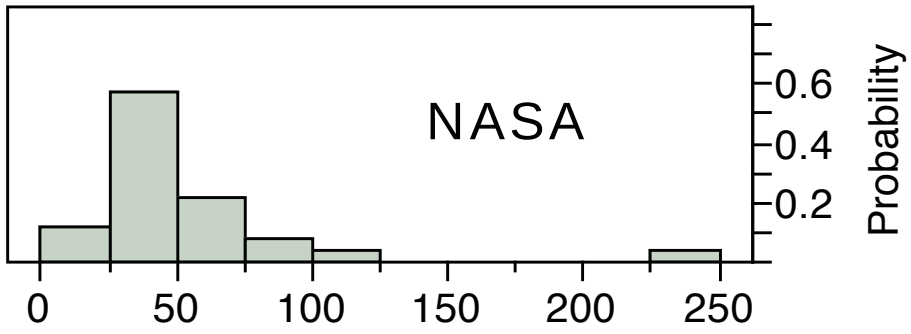
- Miss distances for NASA and MIT-LL perform as expected given their specific DMOD/HMD
- USAF without a miss distance filter at CPA results in larger HMDs

Min. Weighted Slant Range CPA - Miss Distances



- Miss distances for NASA and MIT-LL perform as expected given their specific DMOD/HMD
- USAF without a miss distance filter at CPA results in larger HMDs

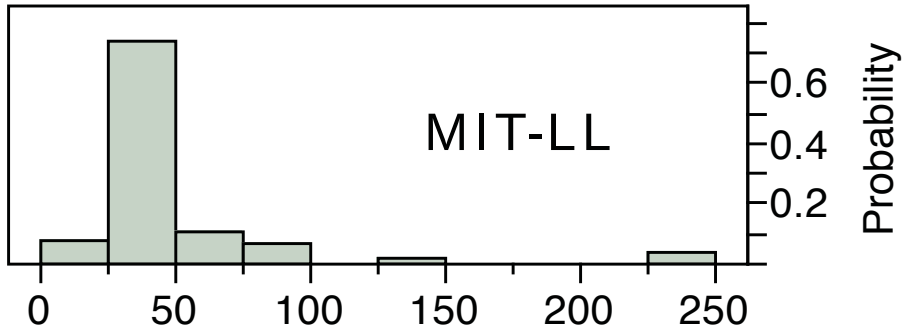
Minimum Time Until NMAC from WCV (sec)



Stats

maximum	238
3-rd quartile	52.5
median	42
1-st quartile	34
minimum	16
Mean	50.0
Std Dev	37.1
N	75

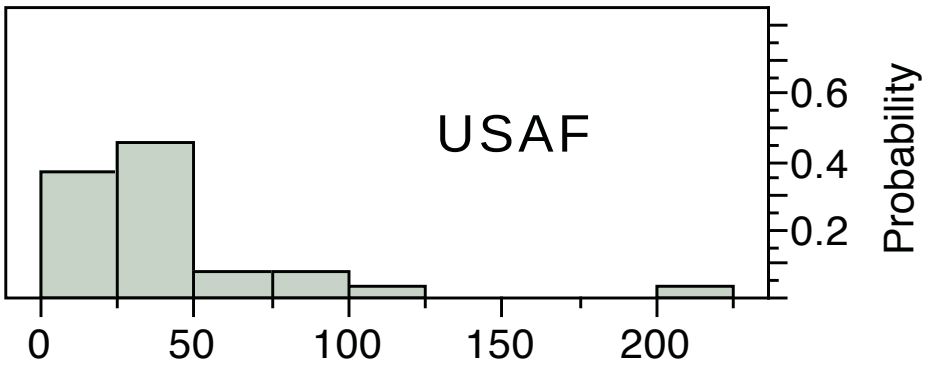
(sec)



Stats

maximum	232
3-rd quartile	47.5
median	40
1-st quartile	36
minimum	18
Mean	49.2
Std Dev	35.9
N	74

(sec)



Stats

maximum	216
3-rd quartile	44
median	28
1-st quartile	20
minimum	8
Mean	40.4
Std Dev	37.2
N	72

(sec)

NASA Min. Time Until NMAC from WCV

- NASA WCV case for minimum time until NMAC, and how it compares to similar case for other WC definitions.

WCD	Time To NMAC (sec)	hSepWCV (ft)	vSepWCV (ft)	modTau (sec)	TCOA (sec)	encAngle (deg)	rDot (knots)	hDot (fpm)	ownAlt (ft)	intrAlt (ft)
NASA	**16**	**11,222**	**476**	**11.7**	**18.2**	**146.4**	**-241**	**-1,572**	**3,036**	**2,560**
MIT-LL	24	16,715	686	22.9	26.1	146.4	-241	-1,572	3,245	2,560
USAF	14	9,849	424	-	-	146.4	-241	-1,572	2,984	2,560

Take-away:

- **Given -1,572 FPM vertical closure rate the MIT-LL WC definition is triggered 8 seconds prior to NASA's, because when violating the TCOA is above 20 seconds (26.1 seconds).**
- **USAF time to NMAC is later due to smaller vSep requirement**

MIT-LL Min. Time Until NMAC from WCV

- MIT-LL WCV case for minimum time until NMAC, and how it compares to similar case for other WC definitions.

WCD	Time To NMAC (sec)	hSepWCV (ft)	vSepWCV (ft)	modTau (sec)	TCOA (sec)	encAngle (deg)	rDot (knots)	hDot (fpm)	ownAlt (ft)	intrAlt (ft)
NASA	22	4,600	842	0	18.9	23.7	-74.0	-2,673	4,858	4,016
MIT-LL	**18**	**3,779**	**666**	**0**	**15.2**	**23.6**	**-72.9**	**-2,616**	**4,734**	**4,069**
USAF	12	2,250	408	-	-	23.5	-71.6	-2,568	4,549	4,141

Take-away:

- **Given -2,673 FPM vertical closure rate the NASA definition is triggered 4 seconds prior to NASA's, because when violating the TCOA is below 20 seconds (15.2 seconds).**
- **USAF time to NMAC is later due to smaller vSep requirement, and large vertical closure rate**

USAF Min. Time Until NMAC from WCV

- USAF WCV case for minimum time until NMAC, and how it compares to similar case for other WC definitions.

WCD	Time To NMAC (sec)	hSepWCV (ft)	vSepWCV (ft)	modTau (sec)	TCOA (sec)	encAngle (deg)	rDot (knots)	hDot (fpm)	ownAlt (ft)	intrAlt (ft)
NASA	36	12,030	337	27.7	0	34.9	-114.2	90.9	1,957	1,619
MIT-LL	36	12,030	337	32.8	0	34.9	-114.2	90.9	1,957	1,619
USAF	**8**	**2,916**	**122**	-	-	**35.8**	**-112.5**	**-345.6**	**1,851**	**1,729**

Take-away:

- **NASA and MIT-LL triggered much earlier than (24 sec) USAF due to modTau**
- **Due to smaller vSep requirement of USAF, and the fact that the ownship and intruder suddenly accelerate towards each in vertical closure rate, time to NMAC is short**
  - **Note, when NASA and MIT-LL WCV triggered, vertical closure is diverging**

Minimum Time Until NMAC from WCV

Final Result

WCD	Min Time Until NMAC (sec)
NASA	16
MIT-LL	18
USAF	8